CNDE Webinar Presentation

February 9, 2023 - 10:00 a.m. CST

This webinar will be recorded and made available on the CNDE website

NASA's Efforts to Improve Nondestructive Evaluation Methods for Additive Manufacturing and in Space Inspection

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NASA's Agency Wide Efforts to improve Non-destructive Evaluation Methods for Additive Manufacturing and In-Space Inspection

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OSMA NDE Development Program Website

Contributors:

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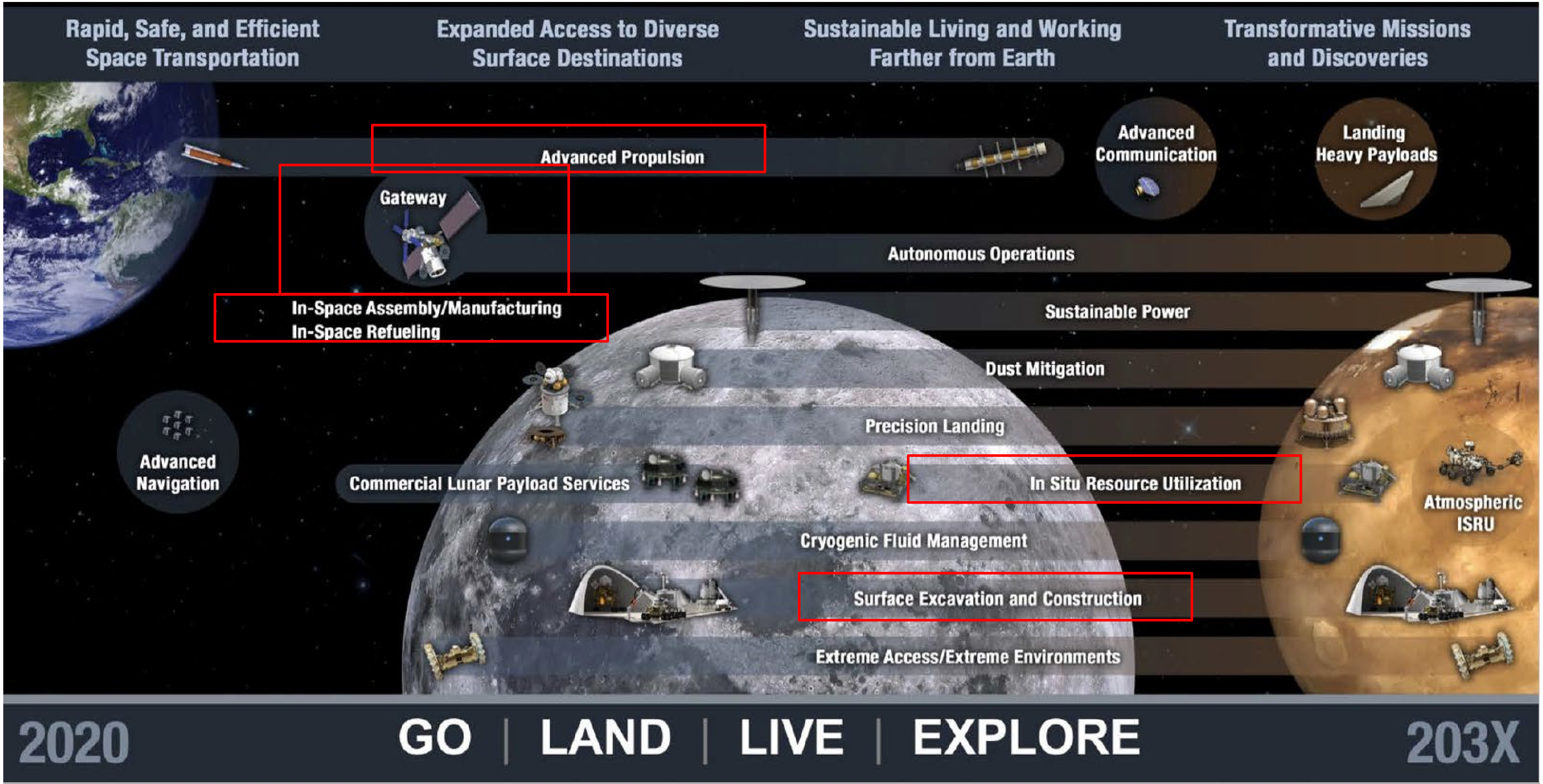
- Douglas N. Wells, NESC Deputy Technical Fellow
  - Materials Damage Tolerance Assessment Branch (MSFC)
- Many Others: Karen Taminger (LARC), Joseph Zalameda (LaRC), Edward Glaessgen (LaRC), Ajay Koshti (KSC), et al.
- Jeannette Plante – Non-destructive Evaluation Program Executive

Technology Roadmap for the Moon and Mars



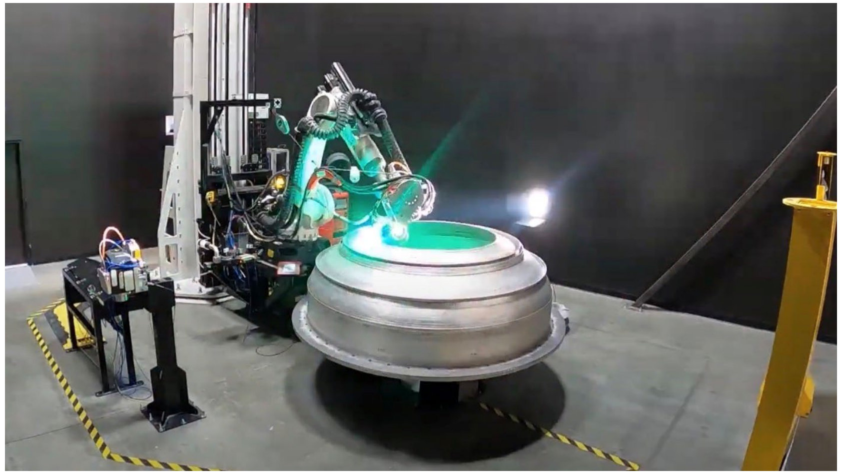
How should this work?

2014 - Space Station 3-D Printer Builds Ratchet Wrench To Complete First Phase Of Operations. It can take months or even years, depending on the launch resupply schedule, to get equipment to space, and for exploration missions, resupply from Earth may be impossible. This technology will change how NASA completes exploration missions and even the way science is conducted on the station.

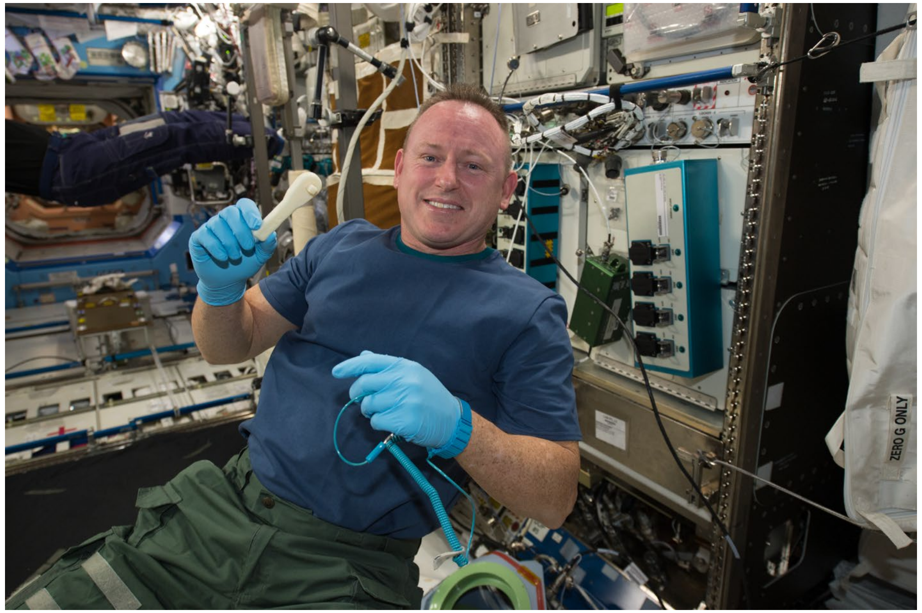
2021 - Relativity Space Terran R project has the audacious goal of 3D printing 95 percent of a rocket and sending it to orbit.

2023 – NASA and its commercial partners are working to certify AM parts for space flight.

Future – Making certified parts in space or other planets.



Its Terran R project rocket nozzle. Terran R is scheduled to launch from Cape Canaveral starting in 2024.



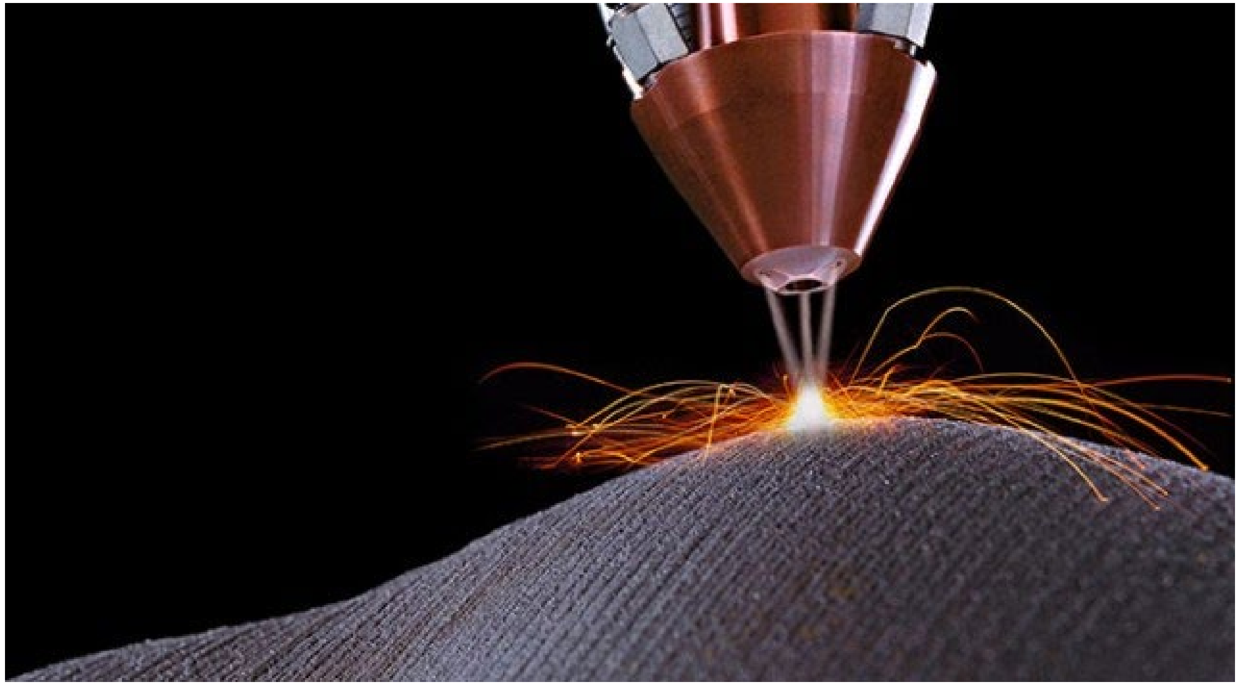
International Space Station Expedition 42 Commander Barry "Butch" Wilmore shows off a ratchet wrench made with a 3-D printer on the station

Presentation Objectives

- During this presentation we will cover a wide variety of subjects from NASA’s activities along the path to Qualification & Certification of Additive Manufactured (AM) Parts for NASA Applications.
- Learn about important AM defect types and how to detect them.
- Review key quality assurance products from MSFC-STD-3716, MSFC-STD-3717, MSFC-STD-6030, MSFC-STD-6033 and AM Handbook.
- Current work and role of in-situ observation during AM builds.
- The role of Nondestructive Evaluation of AM parts at NASA.
- Past and current efforts to improve NDE of AM at NASA.
- Learn about the challenges and best practices for nondestructive evaluation (NDE) of metal AM parts.
- Investigate some unique challenges/applications for AM for NASA. Including in-space inspection.

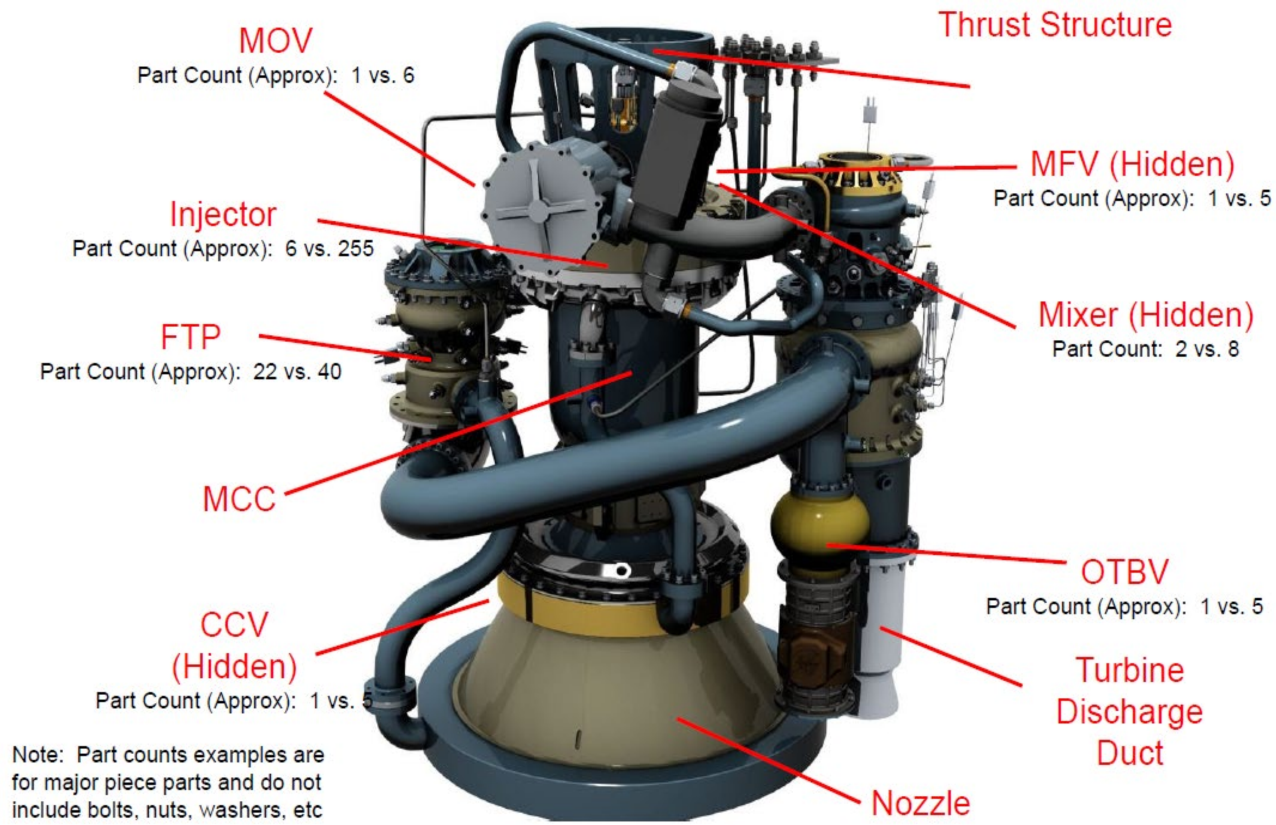
Background

- Additive Manufacturing (AM) is reshaping aerospace design and manufacturing.
- AM processes can be applied to metals, plastics and habitat construction.
- AM is the process of building hardware layer by layer with fewer parts yet more complex designs. This reduces costs and waste while enabling unprecedented design freedom and challenging the order of the traditional aerospace hardware development cycle.



- For existing designs, the cost and time needed to make a part can be reduced, especially for one-of-a-kind or limited quantity production runs common in NASA's programs.
- Repair on the ground and in-space of existing hardware are also a possible future application.
- For new designs, reliance on meticulous analysis to mitigate part failure may be reduced since prototype hardware designs can now be iterated (during Design, Development, Test and Evaluation) with reduced cost and impact to schedule.

Metal Additive Manufactured Hardware Benefits

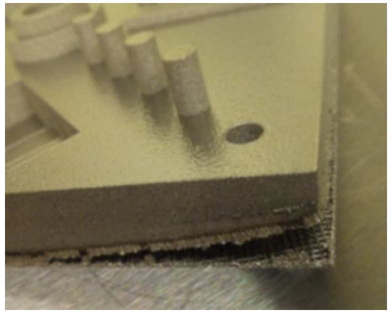


State of the Art for Typical Engine Developments	Prototype Additive Engine
• **DDT&E Time** – 7-10 years	• **DDT&E Time** – 2-4 years
• **Hardware Lead Times** – 3-6 Years	• **Hardware Lead Times** – 6 Months
• **Testing** – Late in the DDT&E cycle	• **Testing** – Testing occurs early in the DDT&E cycle
• **Engine Cost** – \$20 - \$50 Million	• **Prototype Cost** – \$3-5 Million
• **Applicability** – Design for particular mission by a particular contractor – Often proprietary	• **Applicability** – Provide relevant data to multiple customers (SLS, Commercial partners, other government agencies) – Flexible test bed configuration can accommodate other's hardware / design concepts

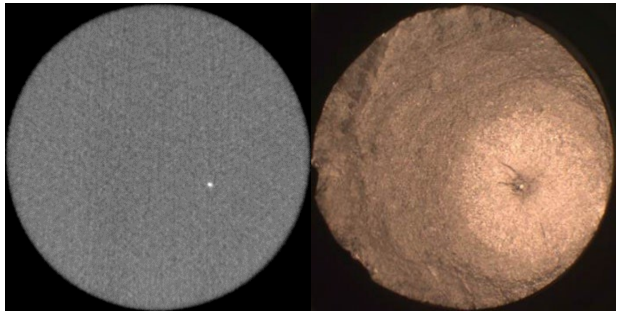
https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160004218.pdf

AM Defects

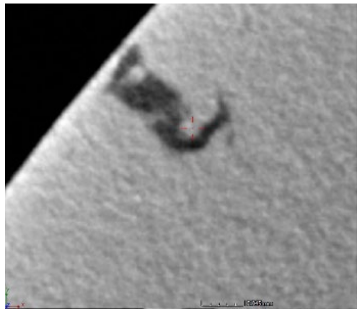
- **General Powder Bed Fusion (PBF) and Direct Energy Deposition (DED) defects** - interested in lack of dimensional accuracy or warping, inclusions, process-induced porosity, gas-induced porosity, and cracks (potential structural implications or out-of-tolerance part):



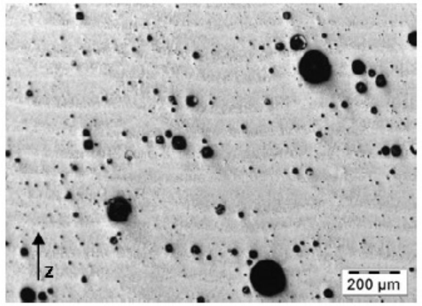
dimensions/warping



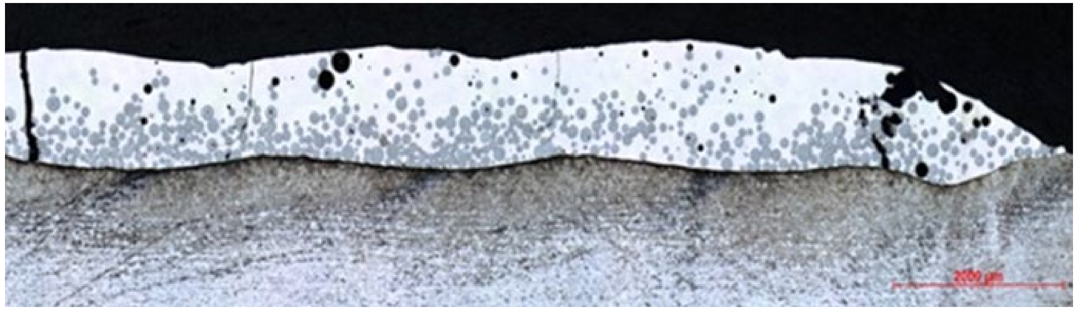
inclusions



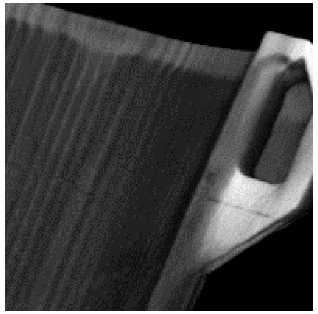
PBF process void



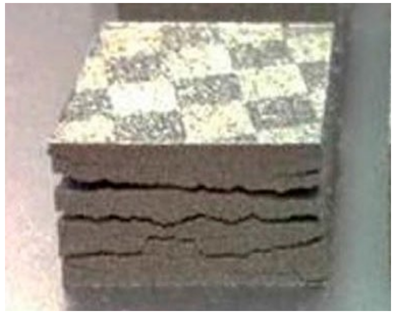
PBF gas porosity



DED gas porosity



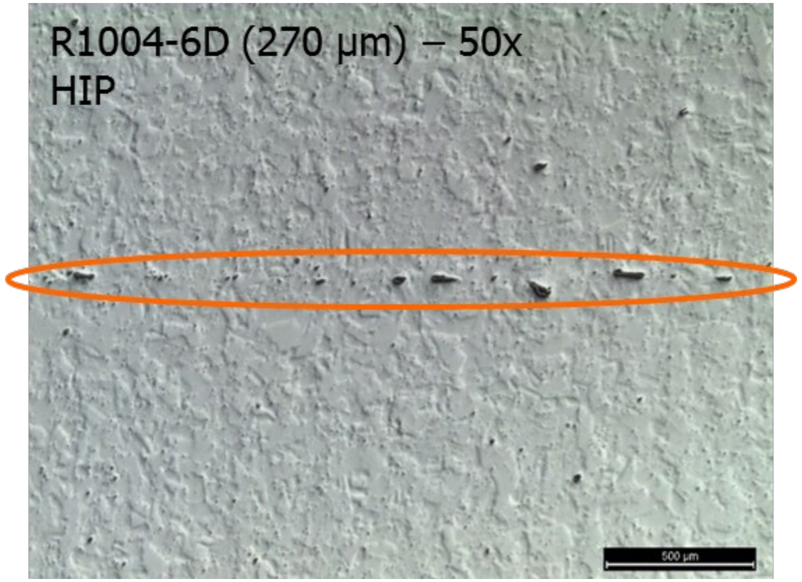
PBF crack



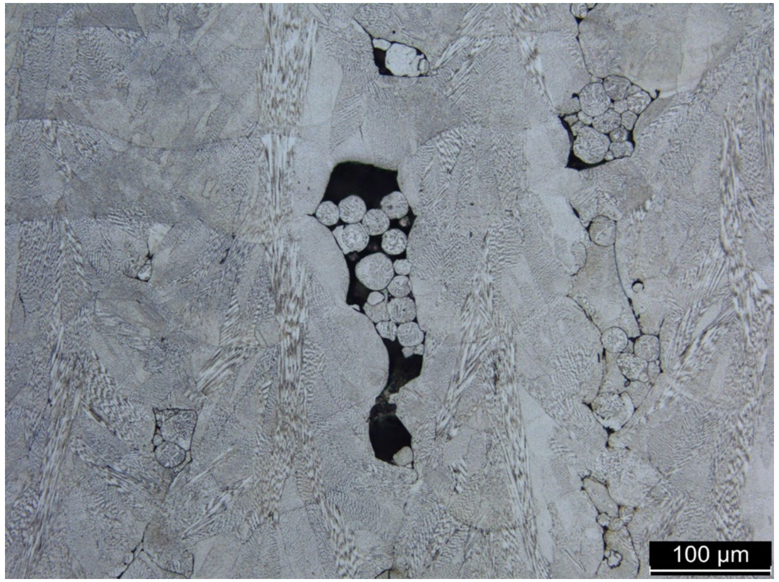
PBF delamination

AM Defects - Cont.

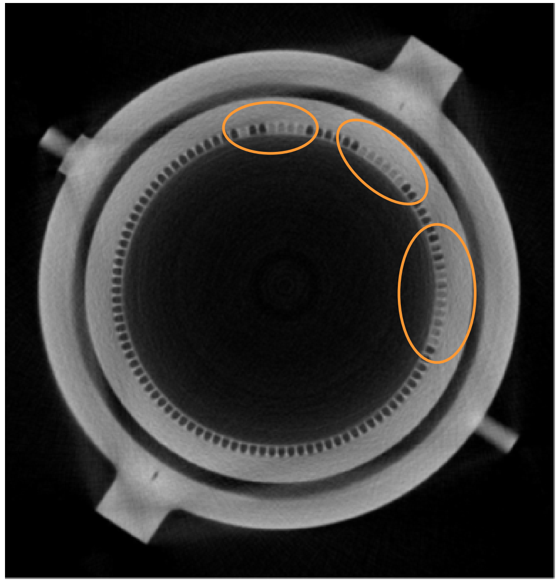
- **Specific PBF defects** – interested in skipped layer/stop-start flaws, lack of fusion (LOF), and trapped powder due to potential structural implications or out-of-tolerance part:



skipped layer/stop-start
(layer defect)

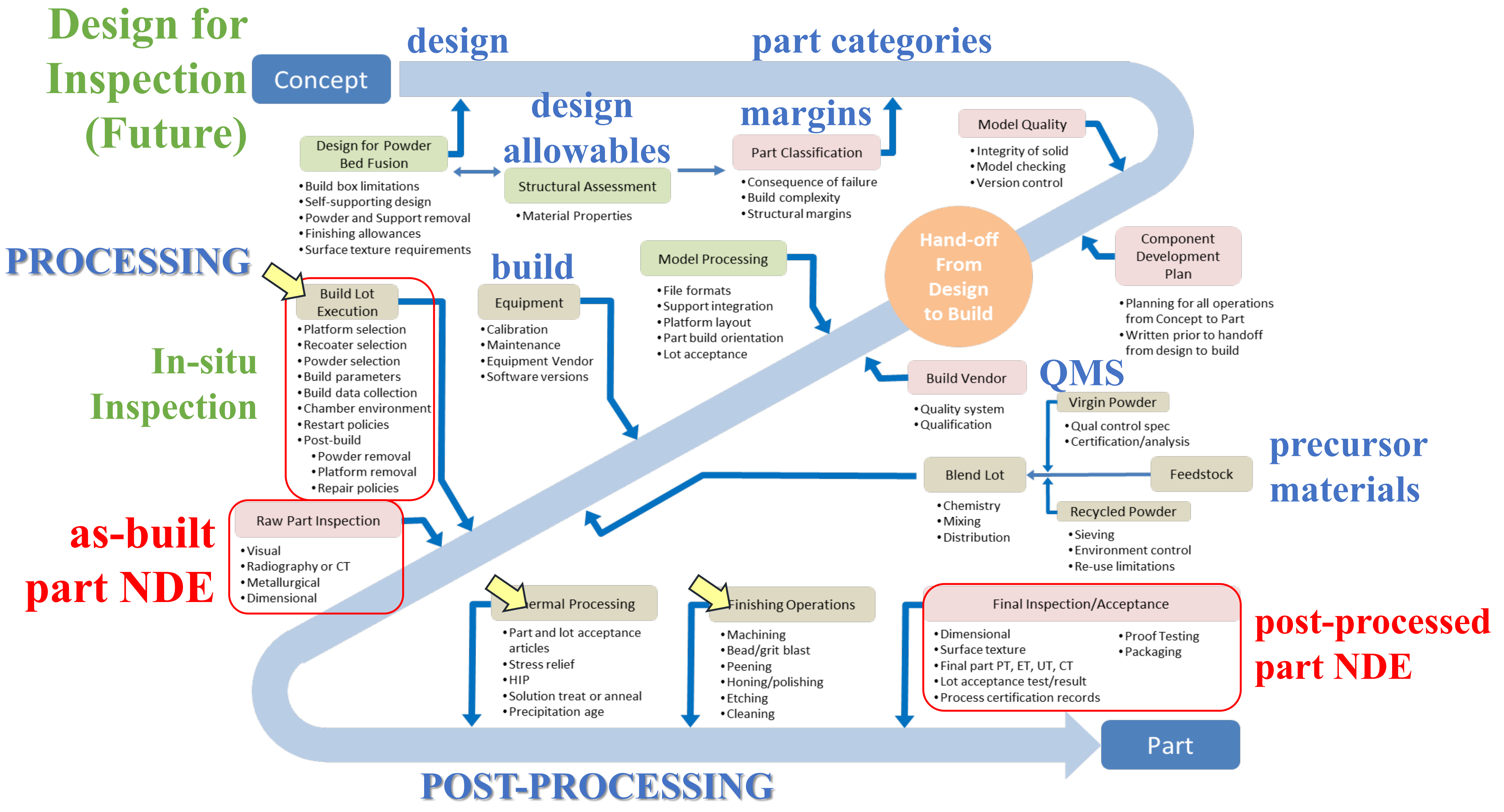


Vertical LOF
(cross layer defect)



trapped powder

Processing and Post-Processing Relative to AM part life cycle



Effect of AM Part Complexity on NDE

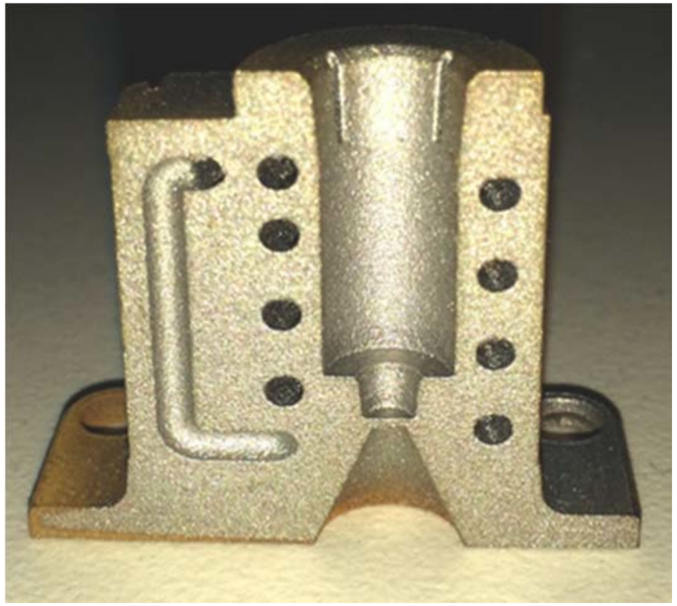
AFRL-RX-WP-TR-2014-0162

- Most NDE techniques can be used for Complexity Group[§] 1 (Simple Tools and Components), Group 2 (Optimized Standard Parts) and Group 3 (Embedded Features):

1

2

3



[§] Kerbrat, O., Mognol, P., Hascoet, J. Y., *Manufacturing Complexity Evaluation for Additive and Subtractive Processes: Application to Hybrid Modular Tooling*, IRCCyN, Nantes, France, pp. 519-530, September 10, 2008.

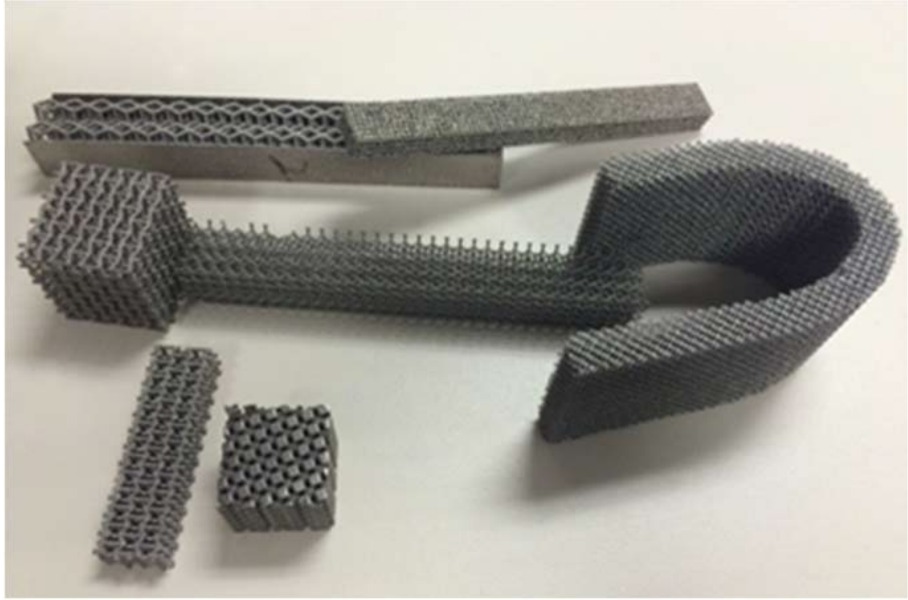
USAF/AFRL-RX-WP-TR-2014-0162 NDE of Complex AM Structures

Effect of AM Part Complexity on NDE
AFRL-RX-WP-TR-2014-0162

- Only Principle Component Resonance Testing (PCRT), Computed Tomography (CT), and Leak Testing (LT) can be used for Complexity Group[§] 4 (Design-to-Constraint or Topology Optimized Parts) and Group 5 (Lattice Structures):

4

5



[§] Kerbrat, O., Mognol, P., Hascoet, J. Y., *Manufacturing Complexity Evaluation for Additive and Subtractive Processes: Application to Hybrid Modular Tooling*, IRCCyN, Nantes, France, pp. 519-530, September 10, 2008.

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Effect of AM Part Complexity on NDE

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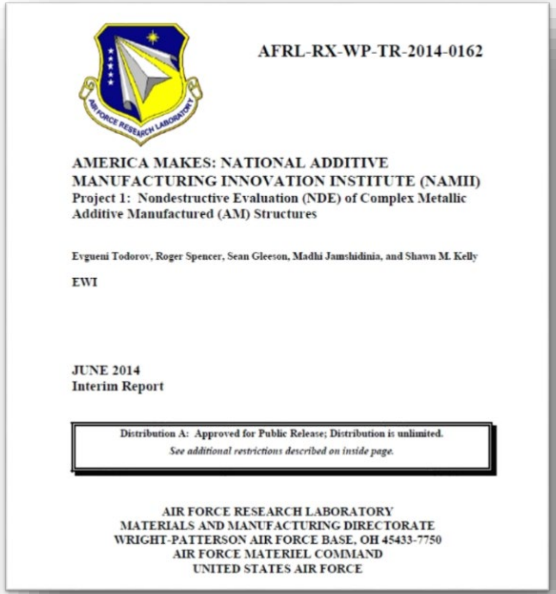

AFRL-RX-WP-TR-2014-0162

AMERICA MAKES: NATIONAL ADDITIVE MANUFACTURING INNOVATION INSTITUTE (NAMII)
Project 1: Nondestructive Evaluation (NDE) of Complex Metallic Additive Manufactured (AM) Structures

Evgueni Todorov, Roger Spencer, Sean Gleeson, Madhi Jamshidinia, and Shawn M. Kelly

EWI

JUNE 2014
Interim Report

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UNITED STATES AIR FORCE

NDE Technique	Geometry Complexity Group					Comments
	1	2	3	4	5	
VT	Y	Y	P(c)	NA	NA	
LT	NA	NA	Y	Y	NA	Screening
PT	Y	Y	P(a)	NA	NA	
PCRT	Y	Y	Y	Y	Y	Screening; size restrictions (e.g., compressor blades)
EIT	Y	Y	NA	NA	NA	Screening; size restrictions
ACPD	Y	Y	P(c)	NA	NA	Isolated microstructure and/or stresses
ET	Y	Y	P(c)	NA	NA	
AEC	Y	Y	P(c)	NA	NA	
PAUT	Y	Y	P(b)	NA	NA	
UT	Y	Y	P(b)	NA	NA	
RT	Y	Y	P(d)	NA	NA	
X-Ray CT	Y	Y	Y	Y	NA	
X-ray Micro CT	Y	Y	Y	Y	Y	

Key:

Y = Yes, technique applicable
P = Possible to apply technique given correct conditions
NA = Technique Not applicable

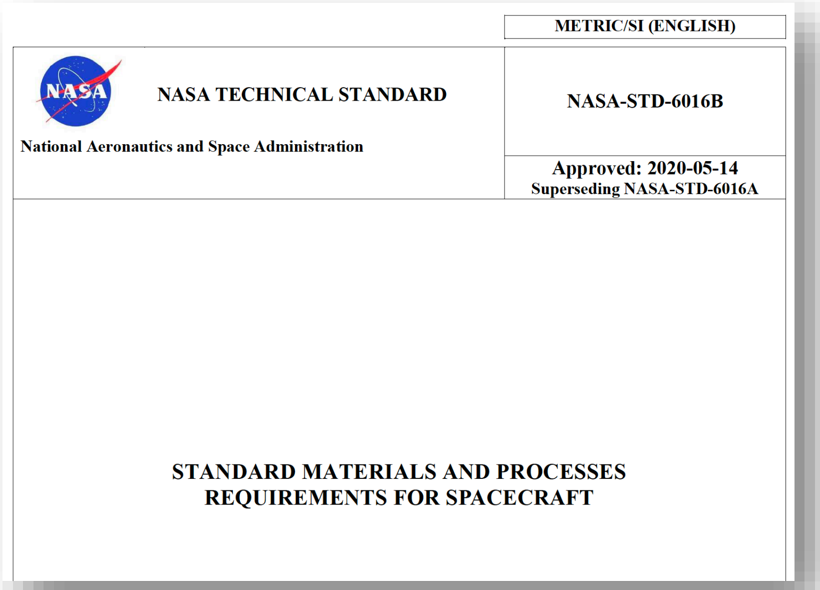
Notes:

(a) Only surfaces providing good access for application and cleaning
(b) Areas where shadowing of acoustic beam is not an issue
(c) External surfaces and internal surfaces where access through conduits or guides can be provided
(d) Areas where large number of exposures/shots are not required

NDE options for design-to-constraint parts and lattice structures: PCRT, CT/µCT, and LT

USAF/AFRL-RX-WP-TR-2014-0162 NDE of Complex AM Structures

Current NASA Standards for Metallic AM


METRIC/SI (ENGLISH)

NASA TECHNICAL STANDARD

National Aeronautics and Space Administration

NASA-STD-6016B

Approved: 2020-05-14
Superseding NASA-STD-6016A

STANDARD MATERIALS AND PROCESSES
REQUIREMENTS FOR SPACECRAFT

NASA-STD-6016B

General M&P requirements

MSFC-STD-3716

Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals

MSFC-SPEC-3717

Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes

NASA-STD-6030

NASA Technical Standard

Additive Manufacturing Requirements for Spaceflight Systems

NASA-STD-6033

NASA Technical Standard

Additive Manufacturing Requirements for Equipment and Facility Control

Handbook coming soon with more specifics on implementation.

Quality Management for AM

NASA has adopted AS9100, Quality Management Systems - Requirements for Aviation, Space, and Defense Organizations, for flowing down quality management system (QMS) requirements to its suppliers. This standard sets expectations for quality controls, process validation, control of external suppliers, and product quality assurance. While these generic requirements will readily apply to parties designing AM parts, building AM parts, supplying specialized capital equipment for manufacturing AM parts, and to raw feed stock suppliers, there remain considerations that are uniquely applicable to AM part production.

Examples are: critical attributes related to raw material production and product acceptance, material storage and handling, second-party surveillance of SPC methods and results, and personnel training. NASA is working with Nadcap and working internally to mature these areas of quality assurance knowledge and practice.

QUALITY MANAGEMENT SYSTEM

AS9100

CERTIFIED

Part Classifications

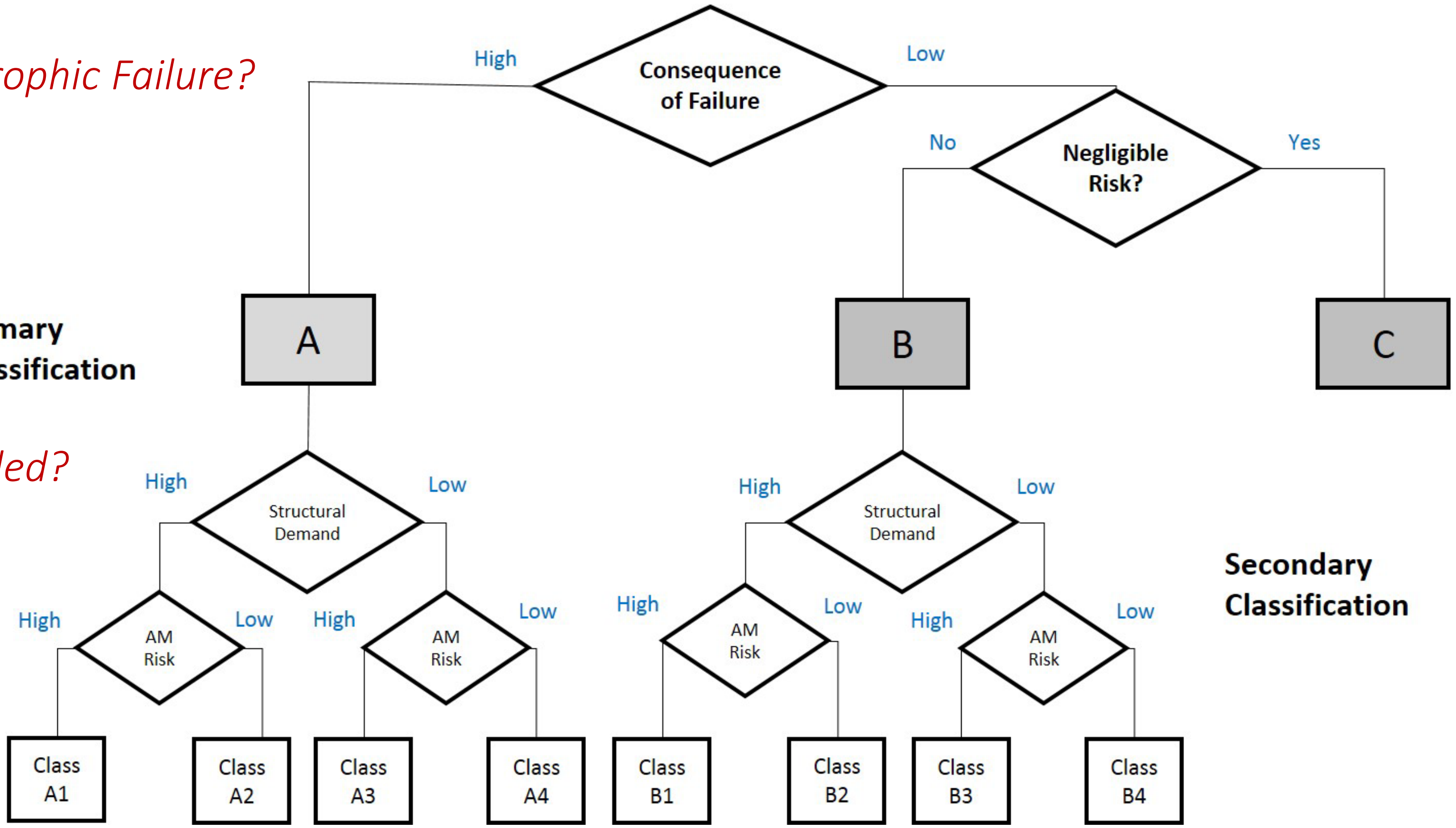
Catastrophic Failure?

Primary Classification

Heavily Loaded?

Does the build have challenging aspects or areas that cannot be inspected?

Secondary Classification



NASA requires quantitative NDE for Class A Parts

Language:

"All Class A parts **shall** receive ***quantitative NDE*** with full coverage of the surface and volume of the part, including verifiable detection of critical initial flaw size in critical damage tolerant parts, with any coverage limitations due to NDE techniques(s) and/or part geometry documented in the Part Production Plan (PPP)"

Rationale:

- "NDE provides a necessary degree of quality assurance for AM parts in addition to the process controls of this NASA Technical Standard."
- "No methodology currently exists to preclude all AM process failure modes through the available manufacturing process controls."

Class A parts, Special NDE requirements in NASA-STD-5009

Language:

"The NDE approach for Class A parts **shall** meet the Special NDE requirements of NASA-STD-5009, Nondestructive Evaluation Requirements for Fracture Critical Metallic Components, and be documented in the PPP."

Rationale:

- "The defects of interest in AM are of a different nature than those listed in Tables 1 and 2 of NASA-STD-5009, and ***AM microstructures can impact the effectiveness*** of NDE methods. Therefore, all inspection of fracture critical AM hardware should be treated as Special NDE."
- "Alternative flaw screening methods for Class A parts (e.g., proof testing) may be feasible with full justification provided in the PPP."

NDE for process Class B Parts

Language:

"All Class B parts **shall** receive ***NDE for process control*** with full coverage of the surface and volume of the part, with any coverage limitations due to NDE techniques(s) and/or part geometry documented in the PPP"

Rationale:

- "NDE for process control requires the use of physical reference standards for calibration and acceptance criteria based on the capability of the NDE technique but does not require quantitative validation of flaw detection."
- "Targeted approaches for NDE can be proposed and approved per the PPP."

Class B parts, the NDE approach NASA-STD-5009

Language:

“The NDE approach for Class B parts **shall** meet the ~~Special NDE~~ requirements of NASA-STD-5009 and be documented in the PPP.”

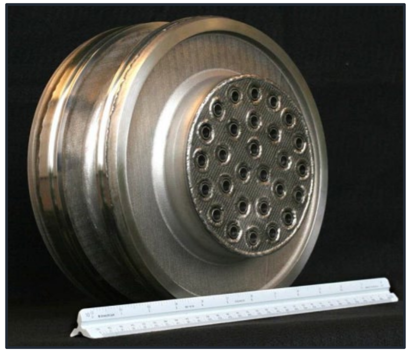
Rationale:

- “The requirements in NASA-STD-5009 establish important controls, including the definition, validation, documentation, and approval of all NDE procedures, standards, methods, and acceptance criteria […]”
- “Alternative post-build quality assurance methods for Class B parts (e.g., proof testing), as well as a reduction in NDE scope for Class B parts, may be feasible with full justification provided in the PPP."

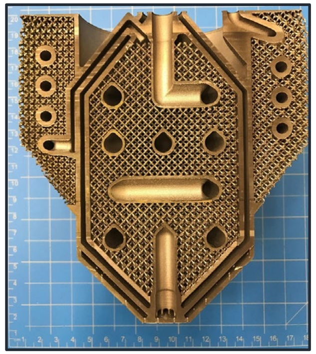
NASA is interested in qualifying in-situ monitoring for complex, critical parts that are difficult to inspect using traditional NDE.

Cryogenic Heat Exchanger-Injector-Condenser Demo

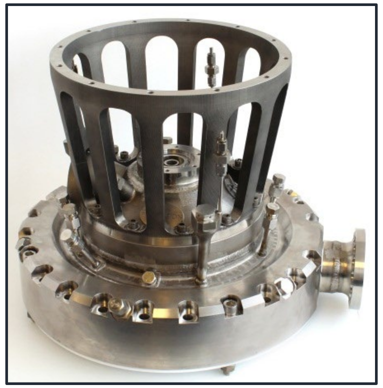
28-Element Inconel® 625 Fuel Injector
Reduced 163 parts to 2
Schedule reduced from 1 year to 4 months
70% cost reduction

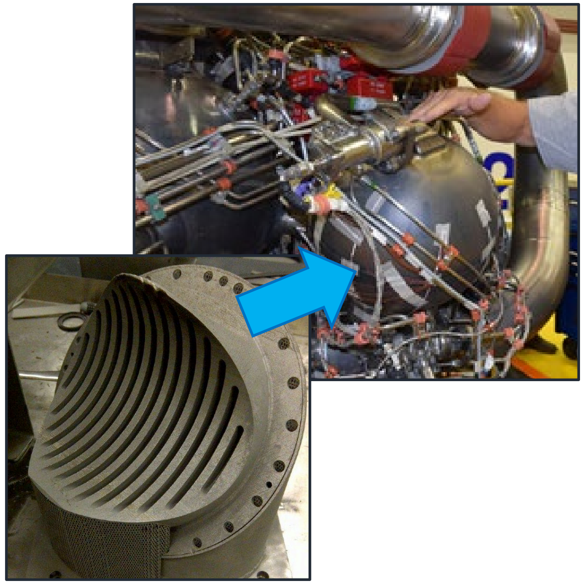
July 2022 – NASA sponsored an ASTM workshop at MSFC





Injector Assembly
MSFC Project with Army Air and Missile Defense (AMD)



RS-25 Pogo Accumulator Z-Baffle
Over 100 Welds Eliminated
Nearly 35% Cost Reduction

Passive in-situ process monitoring

Language:

"Prior to use as a quantitative indicator of part quality for part acceptance, passive in-situ process monitoring technologies **shall** be ***qualified*** by the Chief Engineering Organization (CEO) to the satisfaction of NASA in a manner analogous to other NDE techniques."

Rationale:

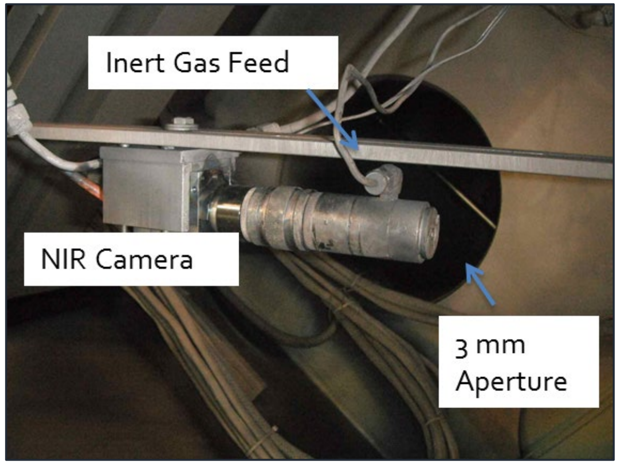
- "All processes that are used to establish quantifiable quality assurance metrics are qualified against established criteria to verify detection reliability, calibration, and implementation. If in-situ monitoring techniques are employed for such purposes, the need for such qualification is unchanged."

Passive in-situ process monitoring may NOT replace NDE.

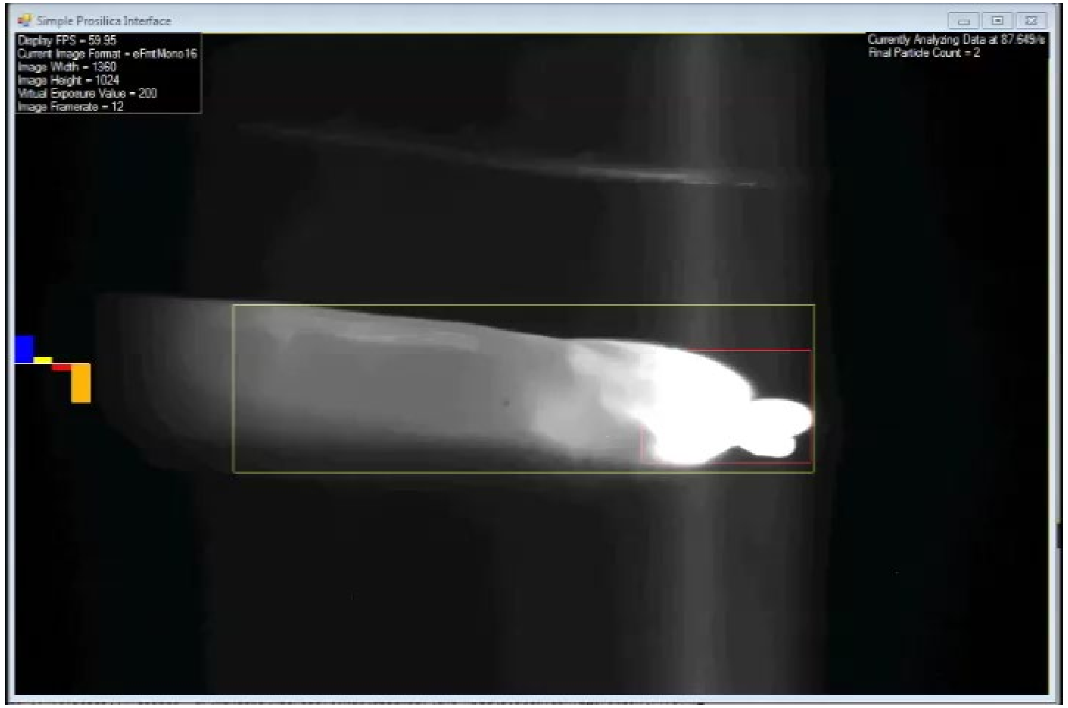
Rationale (cont.):

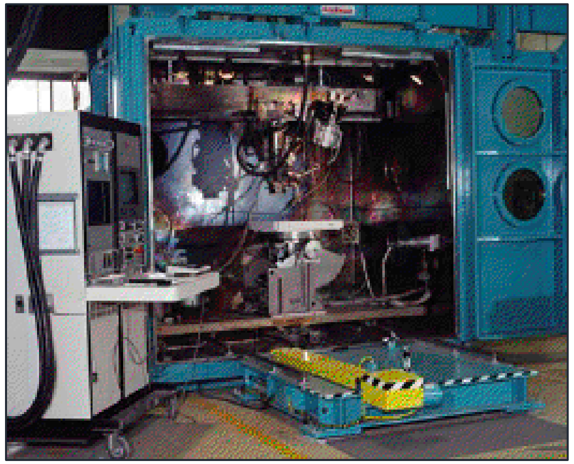
- "Certification of a passive in-situ monitoring technology relies upon a thorough understanding of the physical basis for the measured phenomena, a proven causal correlation of the measured phenomena to a well-defined defective process state, and a proven level of reliability for detection of the defective process state."
- "If qualified in the manner stated above, an in-situ process monitoring technique can be used to complement NDE in the Integrated Structural Integrity Rationale of the PPP. At this time, even a qualified in-situ process monitoring method cannot be considered a complete replacement for NDE."
- "Even if qualification is not desired, the use of in-situ process monitoring is encouraged as a source of process control data. This data can also be used to help guide targeted inspection."

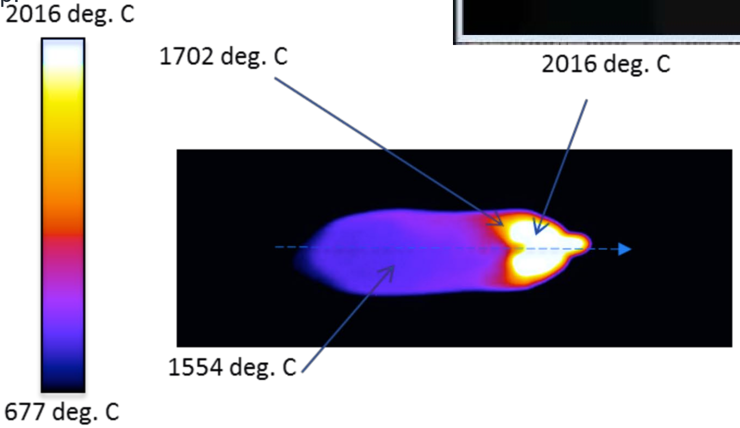
In-situ NDE for Process Monitoring Control

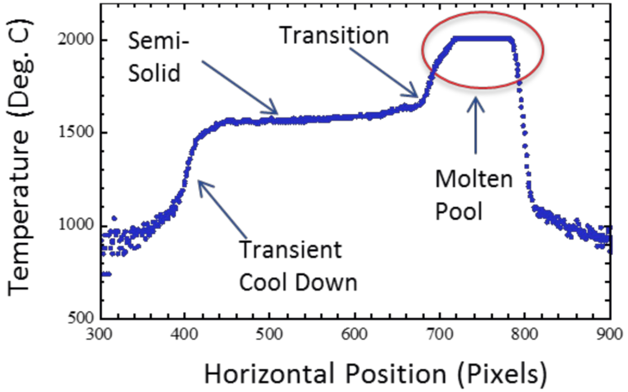


1360 x 1024 array sensor acquired at 30 Hz.
Dynamic range of 12 bits with digital output (GigE) to computer.
Integration time continuously variable from 10 µsec. to 60 sec during acquisition.
Blackbody calibration for Temp.









Overview: The In-Situ Project

- What: The In-Situ Project
  - Correlating In-situ monitoring data and Non-Destructive Evaluation (NDE) methods to characterize defect populations in Laser Powder Bed Fusion (L-PBF) material
- How: Analyze defect detection capabilities of in-situ monitoring by comparison to traditional NDE using flaws created with controlled off-nominal build parameters and verified by metallography
  - Create samples with known defects on EOS M290
  - Record layer to layer AM process quality with EOState Optical Tomography Monitoring system
  - Compare results using North Star Imaging X5000 Mini-/Micro-Focus CT and UES RoboMet serial sectioning system
- Why:
  - Supports developing roadmap for qualifying in-situ monitoring technologies to support NASA-STD-6030 certification approach
    - Proven causal correlation between indications in in-situ monitoring data and final state of the part
  - Supports Agency Lunar Infrastructure objectives

Introduction

- Current L-PBF process, like any process, can generate material that contains defects:
  - gas porosity trapped in the powder feedstock
  - random fluctuations in laser power output
  - error in the build process: skipped layer or short feed
- Defects have detrimental effect on the properties of the material produced:
  - crack initiation sites
  - reduce safe-life of the component
- Traditional NDE methods are not fully adapted to AM:
  - Limitations in reliably detecting defects in large or complex part geometries
- Development of new approach is necessary:
  - Pairing data from in-situ monitoring with NDE

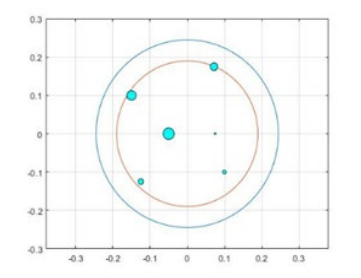
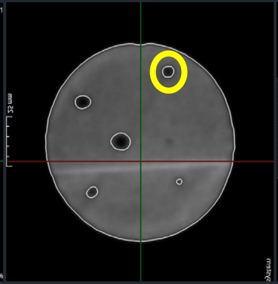
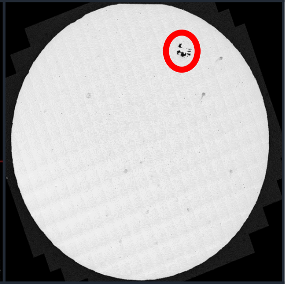
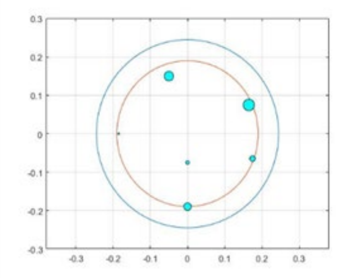
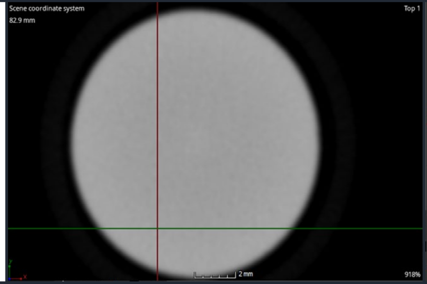
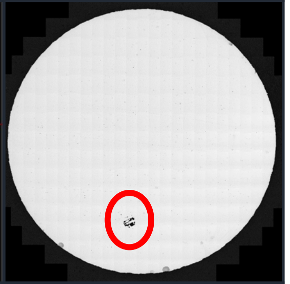
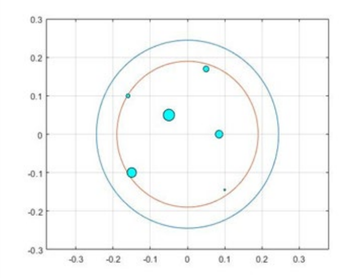
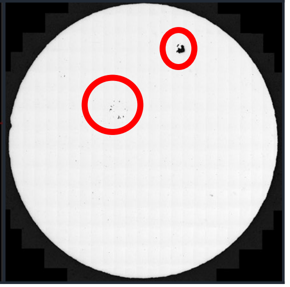
Objectives

1. Develop L-PBF material defect detection and characterization methodologies
2. Understand the influences of build parameter variations on the resulting material defect populations.
3. Correlate detected defect populations with tensile and fatigue properties.
4. Characterize the effect of heat treatment on the defect populations and their detectability with mini-CT.
5. Evaluate part-to-part and build-to-build defect population repeatability.
6. Establish a preliminary probability of detection for the available in-situ monitoring tools and for mini-CT.
7. Evaluate seeded defect methodologies for realistic defect creation.
8. Baseline defect populations for an established AM process as defined in NASA-STD-6030 Qualified Material Process (QMP).

Summary Of Results Build 1 Pre HT

- CT showed no seeded defects
- In-situ monitoring captured an image for every layer showing insertion of seeded defects as designed
- RoboMet slices seeded defect sample at planes 1, 2 & 3
  - 1 or 2 defect remnants per plane: only the higher thicknesses remain

Comparison of Detection Methods for S1-AB-1 (Skipped Layer)

	MATLAB	Mini CT	In-situ	RoboMet
Plane 1				
Plane 2				
Plane 3				

1. S1 samples: Skipped Layer (Unfused Powder) Defects = no power
2. S2 samples: Low Power (Lack of Fusion) Defects = 75% Laser Power
3. S3 samples: High Power (Keyhole) Defects = 125% Laser Power

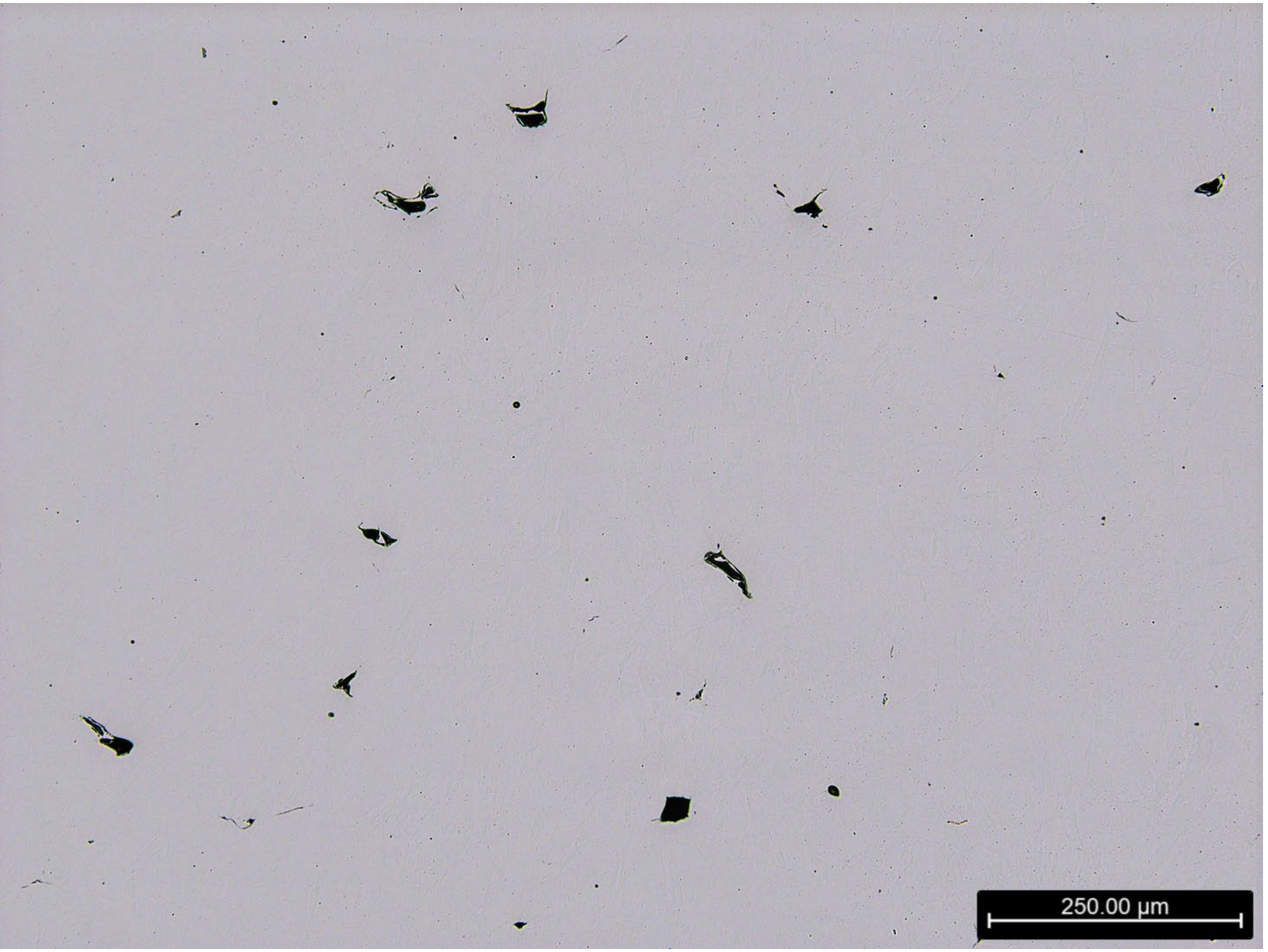
HT: Heat Treated
AB: As Built

Summary of Build 1 Findings

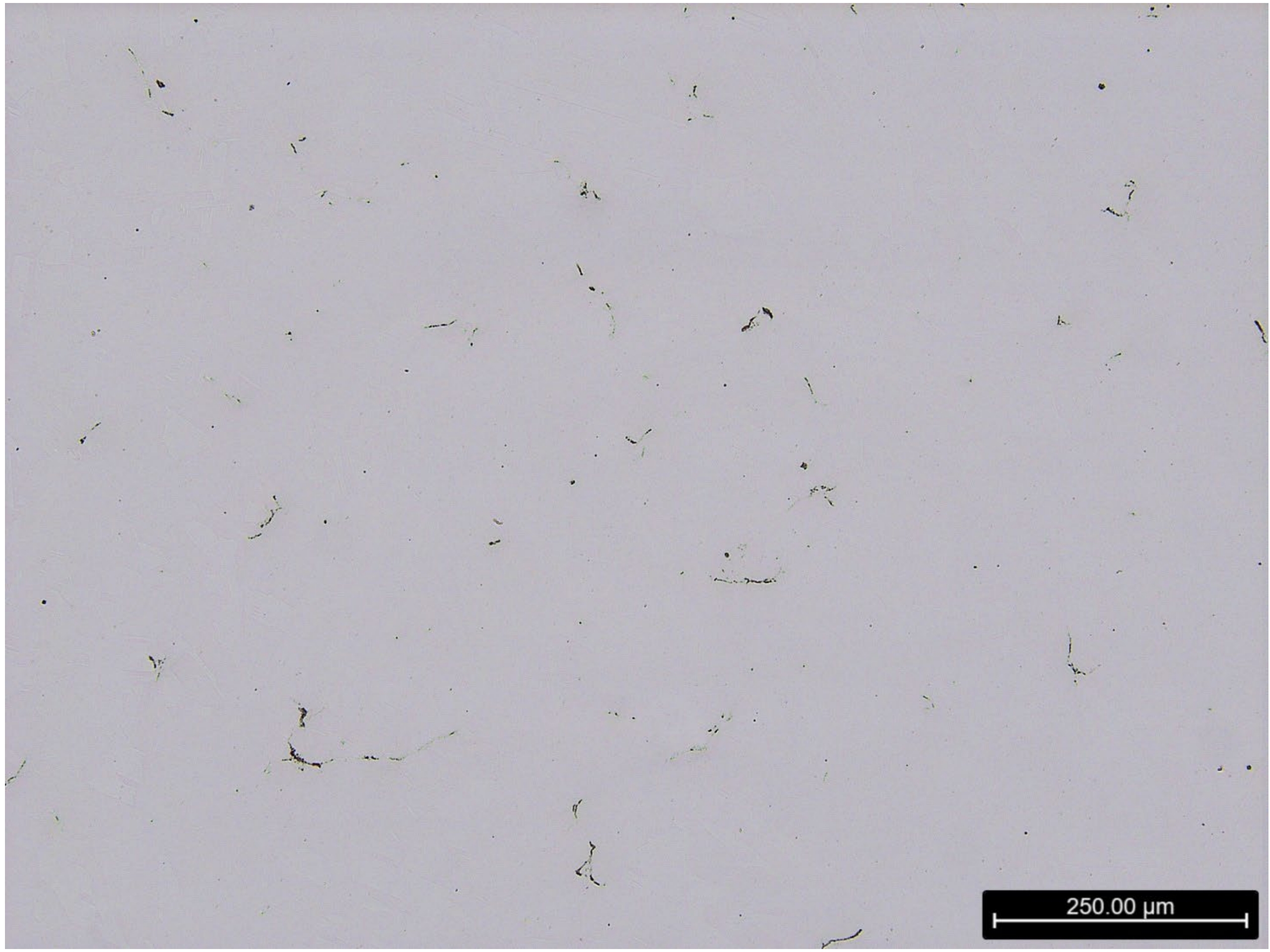
- Seeded defects were not thick enough to be picked up by NDE methods
  - Mini-CT does not offer high enough resolution to pick up that size defect (~0.00315”-0.00945” = 80-240 microns thickness)
  - To be verified with next build with thicker (more layers) seeded defects: 8 to 14 layers
- Defects “heal” during AM build process
  - Meltpool was deep enough that remaining unfused powder within thinner defects melted with the rest of the part, “healing” the sample

All possible Thicknesses (in)	Corresponding Thickness (μm)	Layers	Total defects identified by Robomet	Total defects identified by CT	Out of
0.00315”	80	2	0	0	9
0.00472”	120	3	2	0	9
0.00630”	160	4	2	0	9
0.00787”	200	5	7	0	9
0.00945”	240	6	7	0	9
0.0110”	280	7	9	1	9

75% Laser Power Sample



75% Pre HT



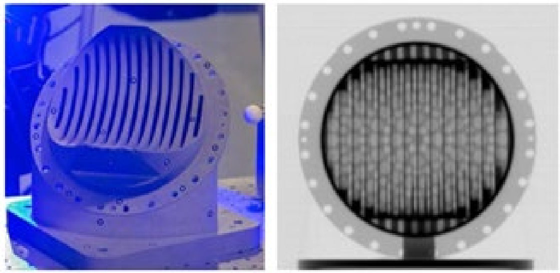
75% Post HT

What's Next?

- How big can we expect a defect to close off after HT?
  - Can we predict based on in-situ data which will close off, which will not?
- Mechanical testing of all those samples and comparing mechanical test w/ nominal parameters
  - Understanding what flaw size will affect the material properties
- Crossing data w/ melt pool monitoring data
- Confirming limitations of NDE tools
  - Minimum flaw size detected
- Calculating probability of detection
  - Based on CT data, current SBIR work to help establish POD of CT.
- L-PBF HR-1 Defect Characterization is just a piece of the bigger in situ project
  - Next step is to practice the methodology on AM complex parts/ propulsion components
  - Study natural flaws in complex geometries (e.g. heat concentration)
  - Machine learning (defect prediction)

Adequacy of NDE Techniques for Additive Manufacturing

Additive manufacturing continues to progress toward use in critical flight structures such as turbo pumps and rocket nozzles. The ability of these metal 3D printers to create complex geometry has outpaced the ability to inspect these geometries. Currently, both NASA and its commercial crew partners are using a single technique, computed tomography, for 99% of additive manufacturing inspection. X-Ray tomography is prohibitively slow for any production environment and is currently inadequate for high reliability crack detection.

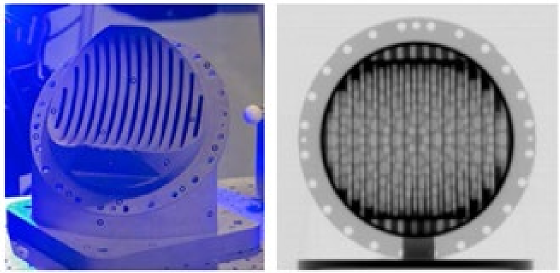


CT Pogo-Z baffles, RS-25/J2-X

- **Office of Safety Mission Assurance (OSMA) efforts on improvements for X-Ray Tomography:**
  - Image quality indicators (IQI) for performance assessments of CT performance.
  - Development of nano-penetrants for improved crack detection.
  - Probability of Detection (POD) using a tomographic system.
- **Ultrasonic Measurements**
  - Phased array & full matrix capture
- **Backscatter X-Ray measurements**
  - 3D BSX on Selective Laser Melting (SLM) Parts

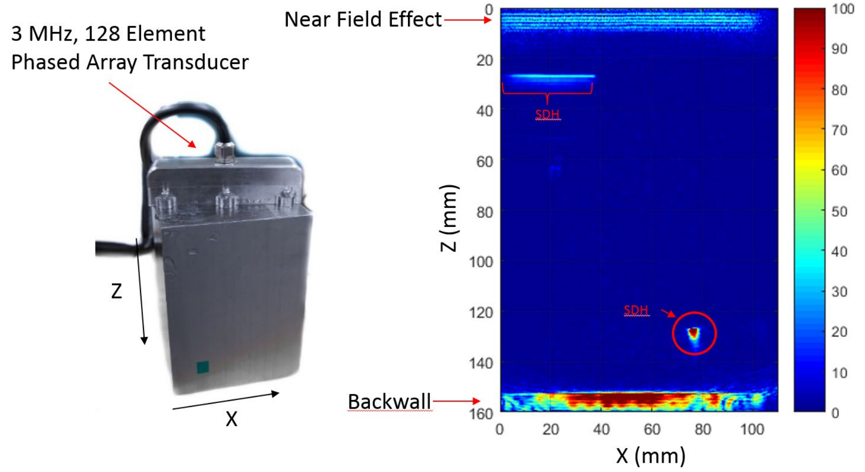
Adequacy of NDE Techniques for Additive Manufacturing – Cont.

- **Modeling and Simulation**
  - Ultrasonic Simulation
  - Monte Carlo Based X-Ray Simulation
  - Automated Intelligent Defect Finding
- **National Standards**
  - NASA is also participating in development of national and international standard developments through ASMT, ASNT as well as JAXA (Trilateral) and ESA.
- **Strategy and Progress:**
  - OSMA current direction is to explore the application of the standard NDE techniques on additive manufactured parts to determine variances caused by the manufacturing technique. OSMA is concurrently participating in the development of standards to ensure proper inspection of additively manufactured parts.


CT Pogo-Z baffles, RS-25/J2-X

OSMA is efforts on improvements for Ultrasonics for Additive Manufacturing:

- NDE analyses of Electron Beam Freeform (EBF)3 samples were completed using both phased array ultrasonics and Total Focusing Method (TFM) Full Matrix Capture (FMC) Inspection.
- Layering anomalies were highly visible in the phased array data.
- TFM & FMC methods preformed better on the EBF block and Signal to Noise Ration (SNR) was significantly improved.

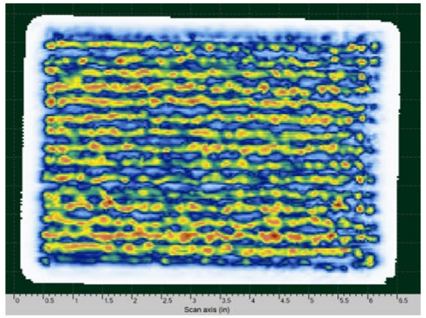


FMC probe and Inside-Out B-Scan

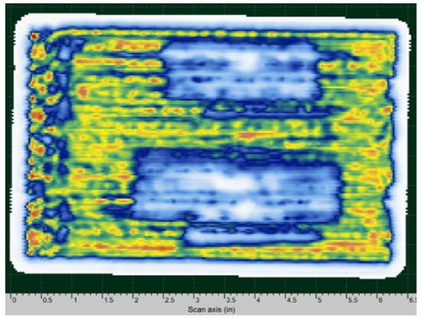
First attempt "Outside-In" block with natural voids.

As-Built

After Machining



Inside-Out Block

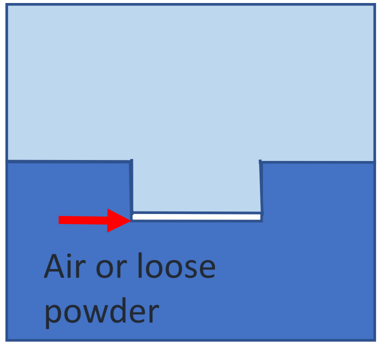


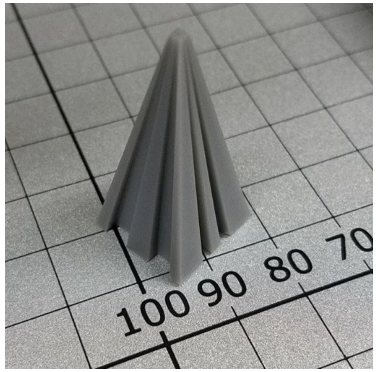
Outside-In Block with Natural Voids

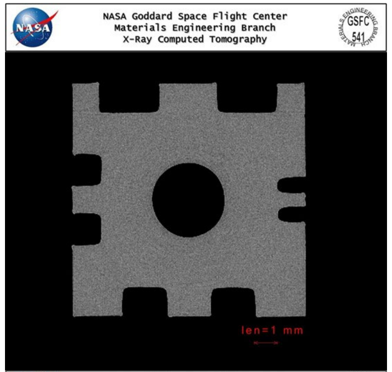
Phased Array Inside-Out (left) and Outside-IN B-Scan

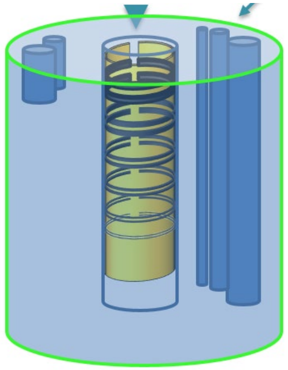
OSMA efforts on improvements for X-Ray Tomography for Additive Manufacturing :

- Image quality indicators (IQI) for performance assessments of tomographic system performance.
  - (“IQIs”): Develop a methodology and set of tools to ascertain Computed Tomography (CT) system performance.
  - (“Reverse Approach/Detectibility of AM Flaws”): Use CT system to characterize AM material build defects and limitations of the CT system to inspect such defects.
- Developments of nano-penetrants for improved crack detection.
  - Magnaflux P-1A filtered particle
- Probability of Detection (POD) using a tomographic system.
  - Currently in work at MSFC working on additively manufactured Inconel 718



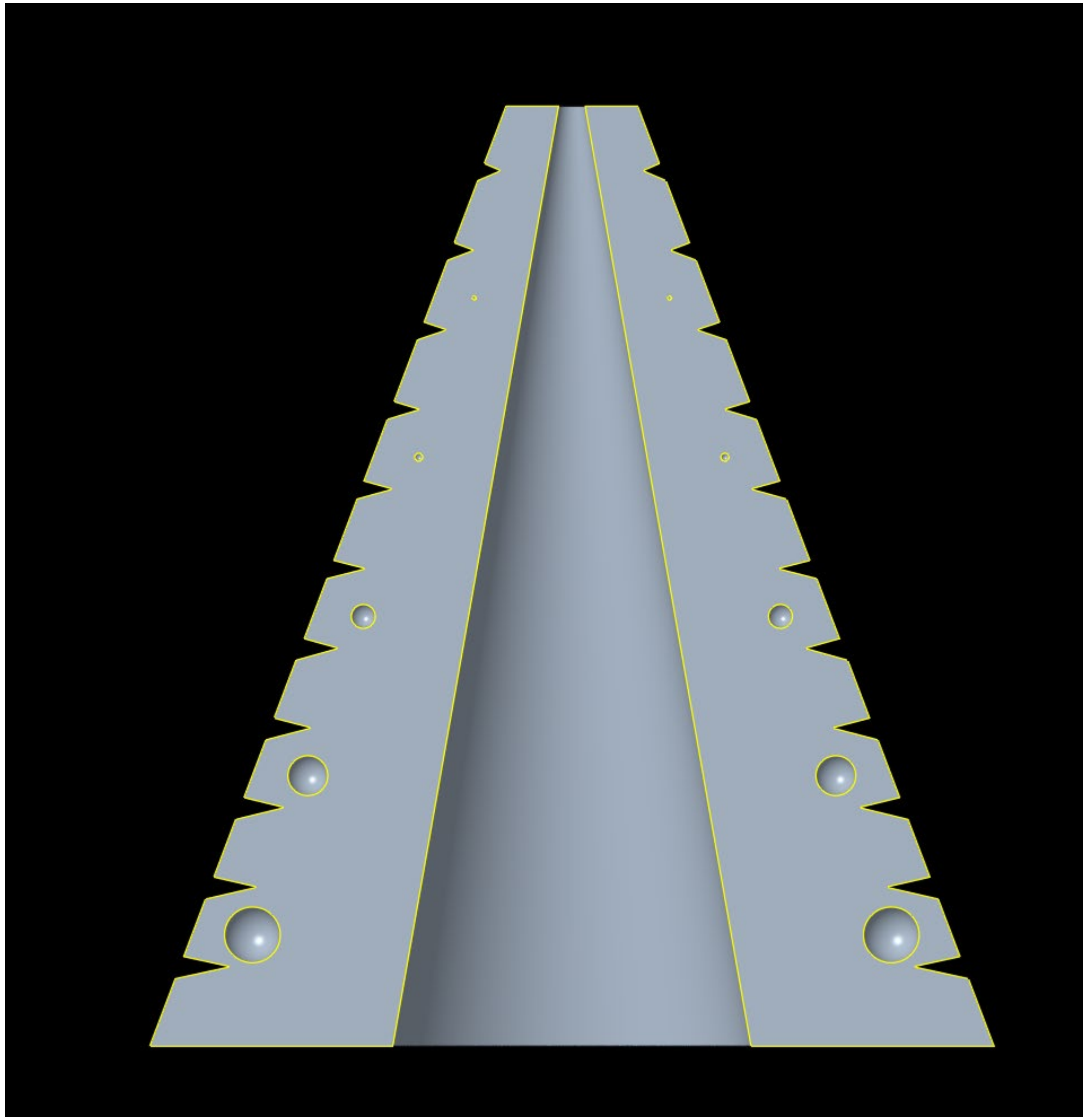






Variations on IQI

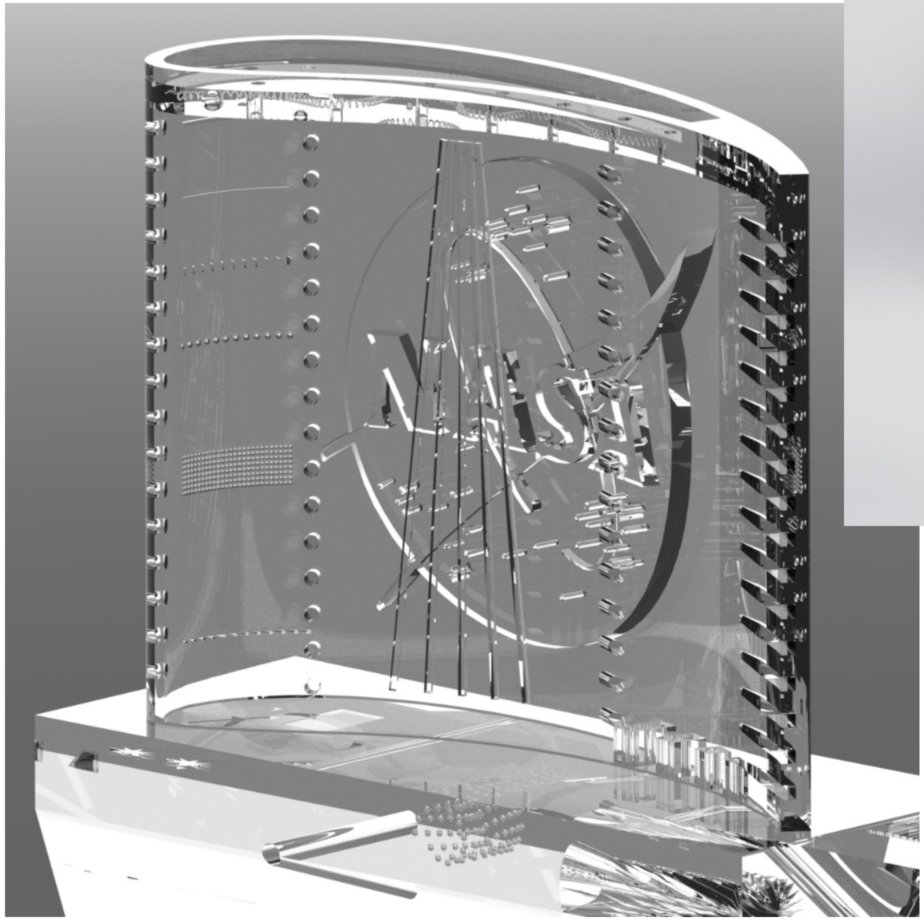
- CT IQI are being included in AM wind tunnel model builds.
- This modified version of the NDE IQI helps to ensure build quality but has built in spheres to trap powder for post build analysis.

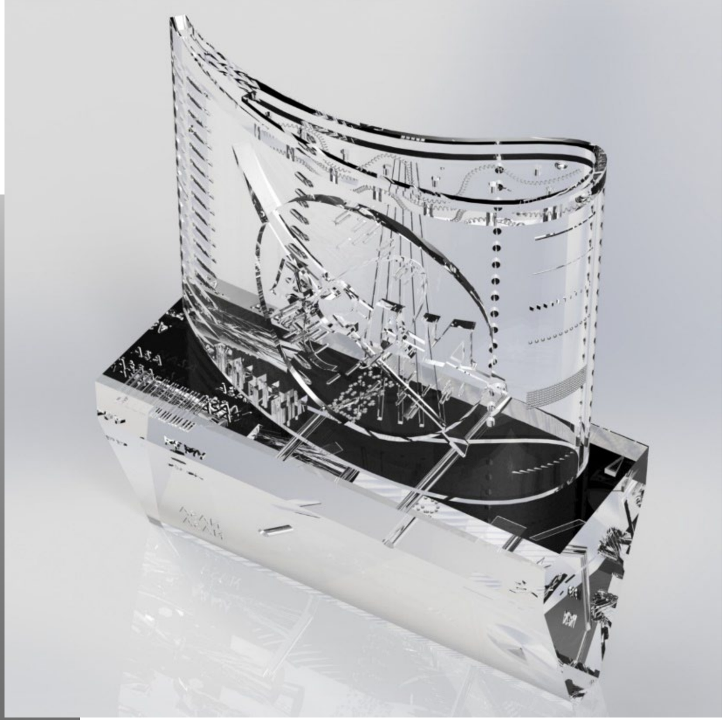


Other NASA NDE Samples

NASA designed an NDE specific sample designed to test multiple NDE techniques as part of student challenge for the 12th International Symposium on NDT in Aerospace 2020. Sample design has been made publicly available.

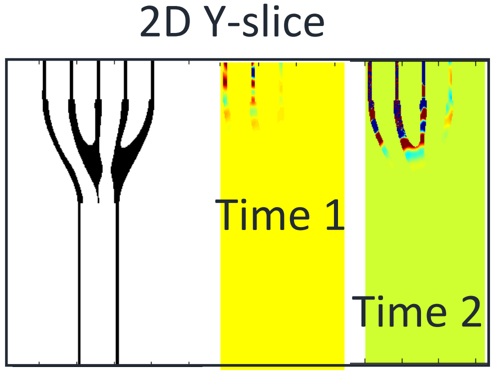
- Some of the features include:
  - Internal X-Ray resolution gauges
  - Blocking and Calibrating defects
  - Defects that are directional dependent
  - Defects that are method dependent





OSMA is efforts on improvements for Modeling and Simulation for Additive Manufacturing:

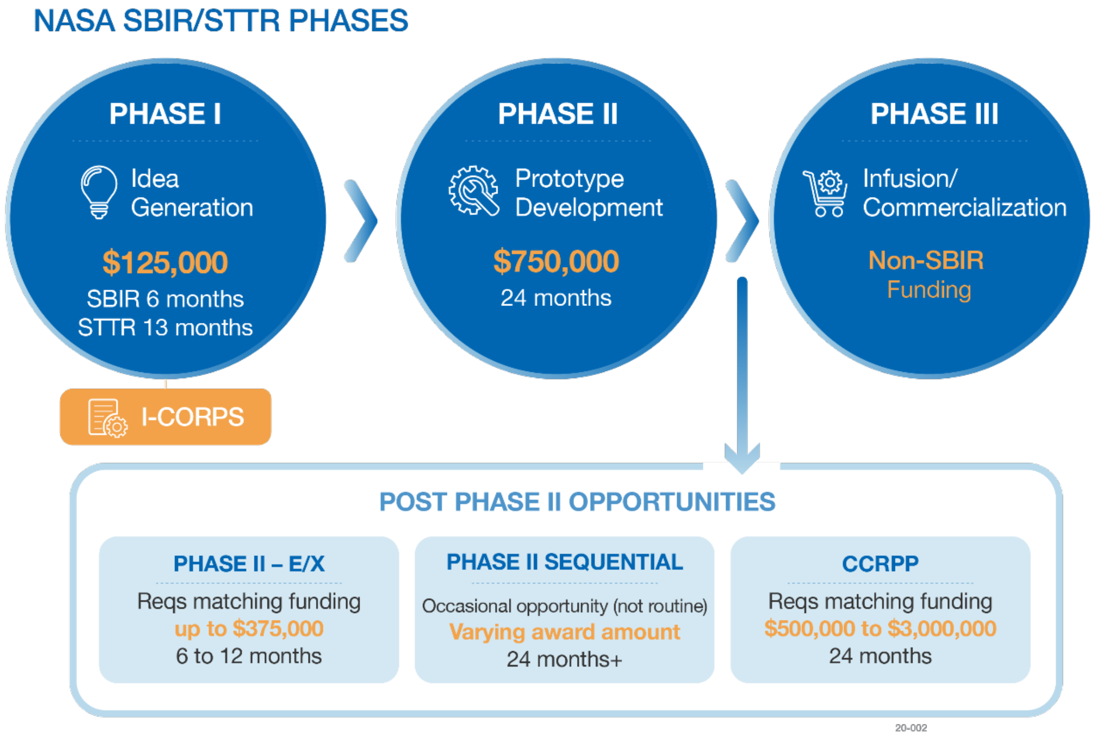
- OSMA and Langley NESB have teamed to make physics-based simulation models available to the entire agency.
- Although are looking at other simulation codes and software CIVA to determine the best package for multi-technique physics-based simulation and was the package chosen to make available agency wide.
- CIVA is currently being used to help establish POD work by the NESC and others.



Demonstrated Process Flow for Cad to Modeling Code

SBIR Overview

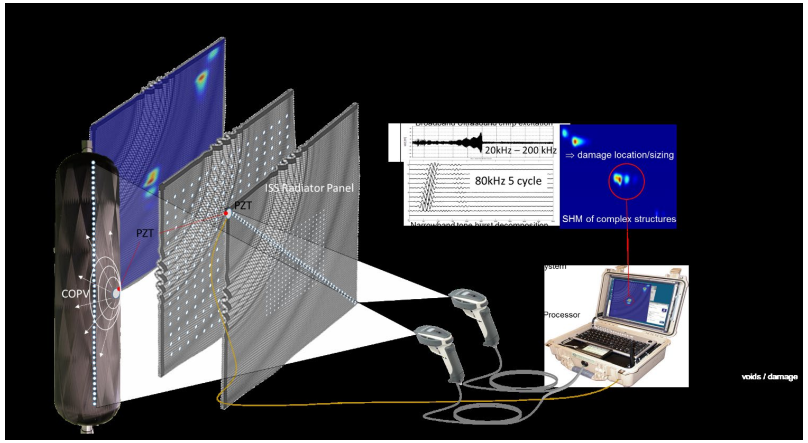
- The NASA SBIR and STTR programs fund the research, development, and demonstration of innovative technologies that fulfill NASA needs as described in the annual Solicitations and have significant potential for successful commercialization. If you are a small business concern (SBC) with 500 or fewer employees or a non-profit RI such as a university or a research laboratory with ties to an SBC, then NASA encourages you to learn more about the SBIR and STTR programs.
- NASA has selected 409 technology proposals for the first phase of funding from the agency's Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) program. The contracts will provide approximately $51 million to 312 small businesses in 44 states and Washington, D.C.



https://sbir.nasa.gov/content/nasa-sbirsttr-basics

Nondestructive Evaluation SBIR Overview Highlights

- NASA NDE community has been very active in the NASA Small Business Innovation Research (SBIR) Program for the past decade.
- Since 2010 NDE has had over 68 phase 1 and phase 2 awards and we have participated in an additional 37 from other subtopics. For a total of 105 Phase 1&2's
- Several of these prototypes are currently deployed to help the Artemis program achieve its goals.
- The SBIR Topic, Subtopic, Contracting Officer Representative (COR'S) and reviewers come from 7 of the major NASA centers.
- NASA technical experts for the are the reviewers for all the proposals and generally take 2-3 months to complete the review process.
- Several of these have been in-situ monitoring systems and studies on POD for CT.
- Not covered here but there are also several impact monitoring systems that are in work and currently deployed.



Opportunities for Investment and Collaboration

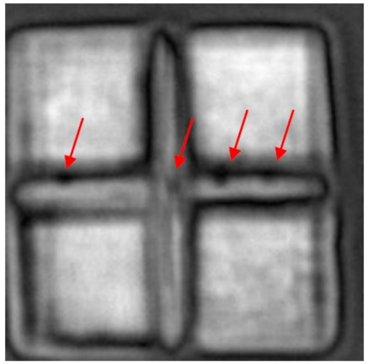
- The NASA NDE community has been very active in the NASA (SBIR) Program for the past decade.
  - Since 2010, NDE has had over 73 phase I and II awards.
  - NASA technical experts are the reviewers for all the proposals and generally take 2-3 months to complete the review process.
  - Several awards have funded prototypes that are currently deployed to help Artemis and other programs achieve their goals.

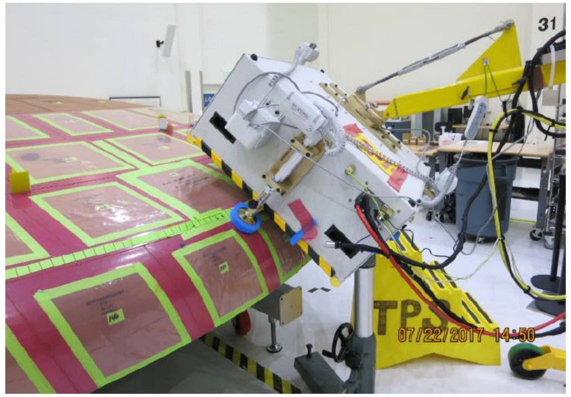
- **SBIR/STTR call for proposals is a great place to learn what "NDE Tools" are needed by NASA, as well as what sort of materials challenges are currently relevant**

Recent Award:

UES and PSU-ARL won SBIR Phase 2 for "Probability of Detection and Validation for Computed Tomography Processes for Additive Manufacturing". Using Robo-Met as ground truth for CT qualification.

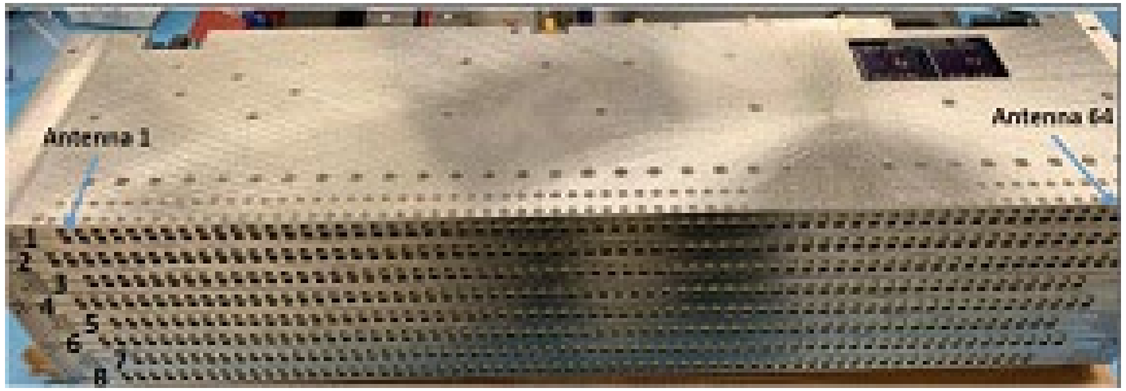
Past Highlight:





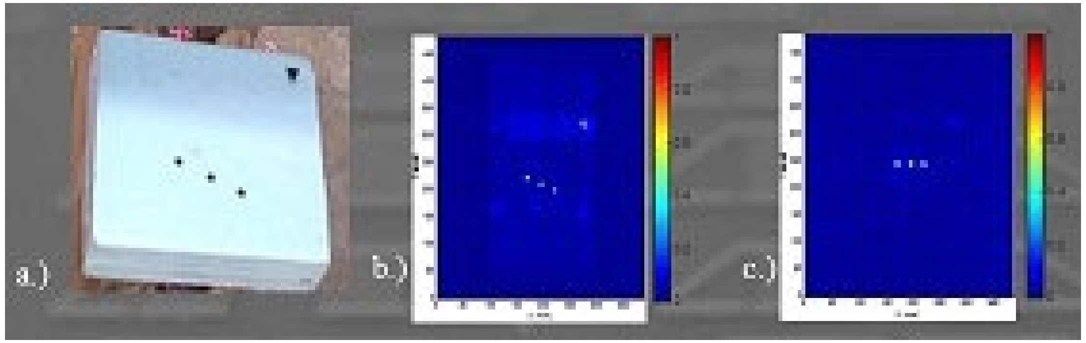
Physical Optics Corp (POC), 3D backscatter unit (single-sided CT) deployed to KSC to preform thermal protection system gap inspection.

3D Microwave Imager for Damage Detection



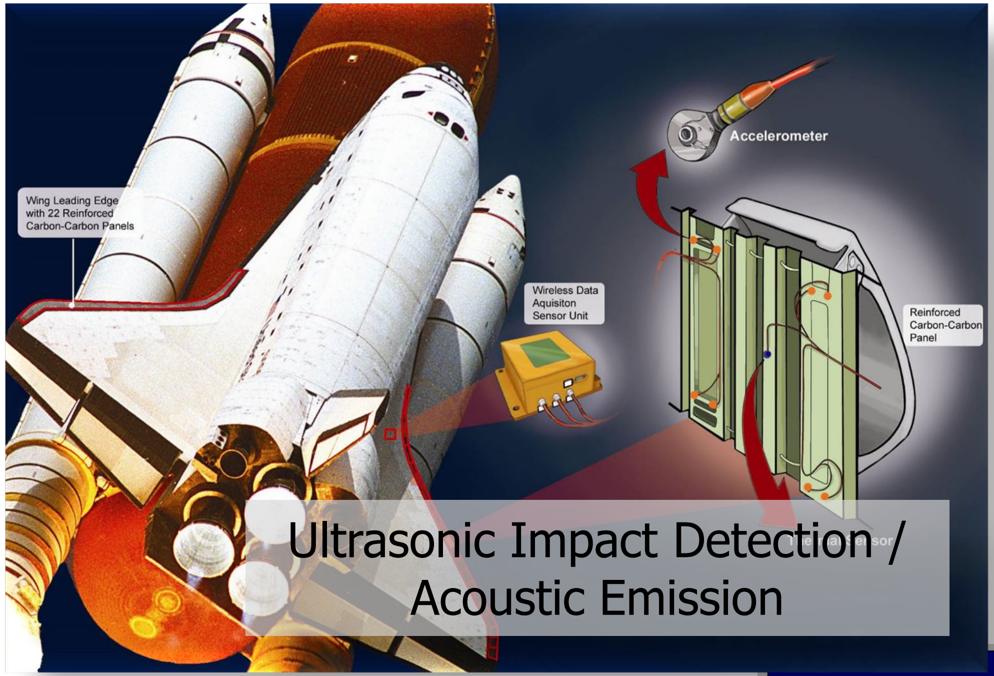
TRI and ISU's multi-static imaging array developed in the Phase II SBIR effort consisting of 8 linear arrays, each with 64 antennas (width is ~ 16").

- In a Phase II SBIR effort, TRI and ISU produced a Millimeter wave SAR imaging system.
- Provides high-resolution three-dimensional (3D) images.
- The system has 8 linear arrays, each containing 32 transmitting and 32 receiving antennas (512 total) and performs multi-static measurements.
- Operation frequency range of 26.5–40 GHz. Cross-range resolution (lateral directions) of ~2.5 mm and an along-range resolution of ~9.4 mm (depth direction).
- Resolution figures are calculated for vacuum (or air) and the resolution increases inside dielectrics.
- Sample image-set shown of a foam calibration block with embedded rubber targets.
- Using the SAR algorithm, 2D image slices were generated from the 3D data.
- Was recently awarded a phase 2E



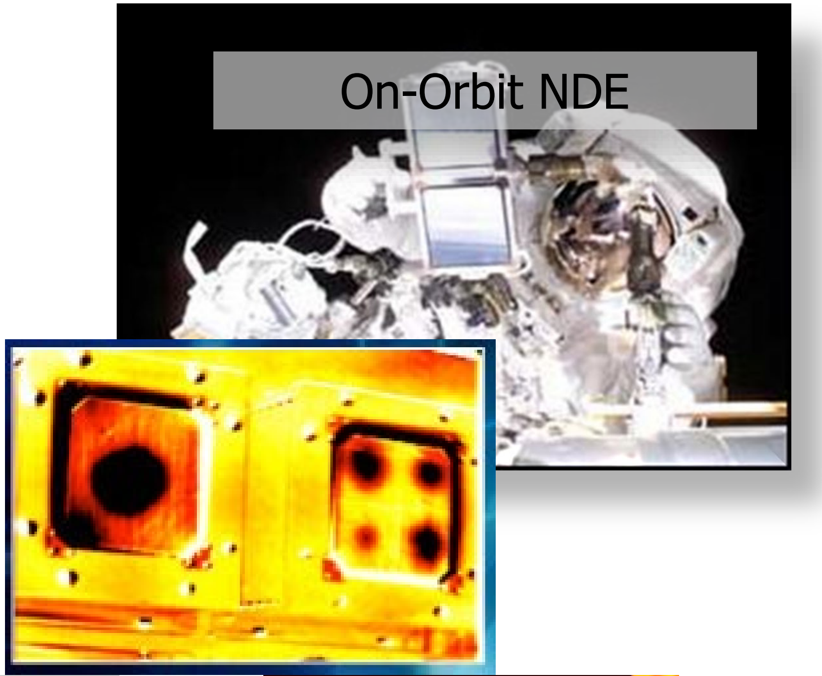
(a) Foam calibration block with embedded rubber targets and 2D slices of the Ka-band (26.5-40 GHz) 3D SAR image at two depths; (b) surface of tile and (c) 25 mm deep.

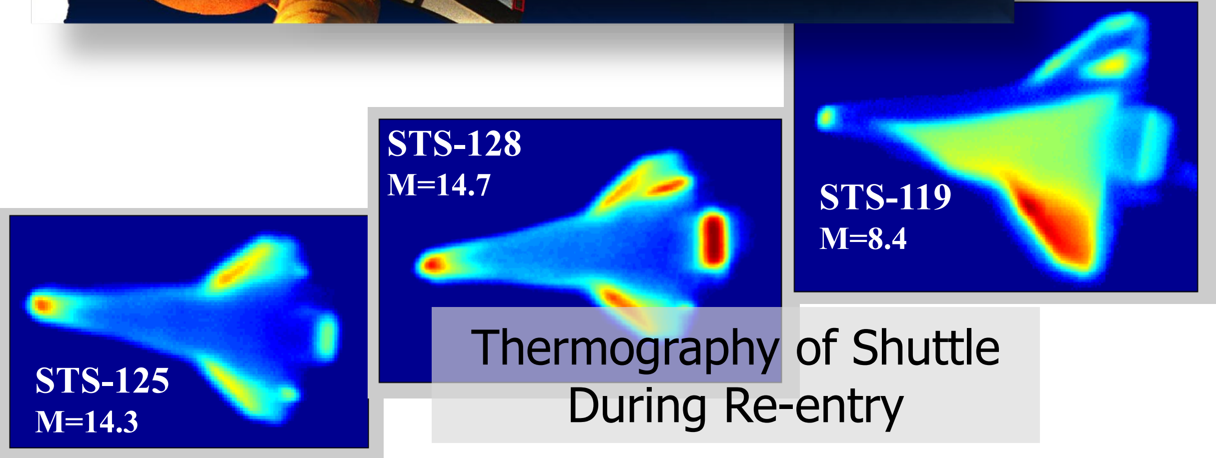
Human Space Flight Support



Ultrasonic Impact Detection / Acoustic Emission

On-Orbit NDE





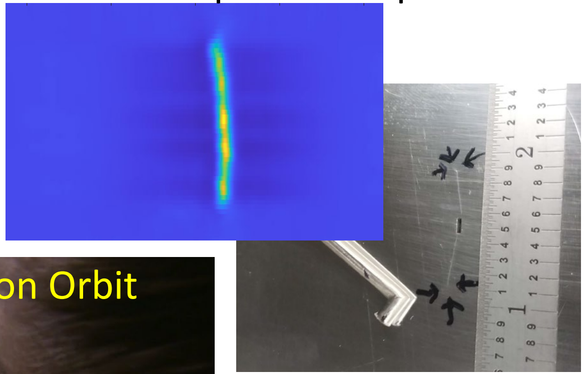
Thermography of Shuttle During Re-entry

Capability Advancement and Top Concerns

Eddy Current development for crack detection and characterization on ISS

- Air leak on the Russian Transfer Tunnel of the ISS resulted in the discovery of a fatigue crack in the aluminum shell of the structure
  - Crack appeared to be ~ 20mm long. Increasing leak rate suggested crack growth over time.
  - LaRC contacted in October 2020 for assistance in characterizing crack damage.
- Eddy Current inspection proposed as on-orbit crack detection and characterization tool
  - Representative samples fabricated and characterized with proposed eddy current techniques.
  - Results presented to ISS Structures and Mechanical Systems Team which recommended delivery of equipment to ISS.
- Eddy Current inspection equipment and techniques delivered to ISS
  - LaRC and JSC engineering developed specification for required equipment.
  - Techniques and procedures finalized for detection of cracks, location of crack tips, and measurement of shell wall thickness.
  - Procurement, lead by JSC, performed in time to meet launch schedule for Resupply Mission SpX-21 in December 2020.
- On-orbit Inspections performed March 2021.
  - Crack length and crack tip locations successfully characterized.
  - Wall thickness measurements performed finding nominal conditions.
  - Other surface features examined and determined to be superficial scratches.
- Procedure for measurement of crack depth along the flaw in work.
- Multi-Center Program
  - Langley, JSC, NESC

Technique Development



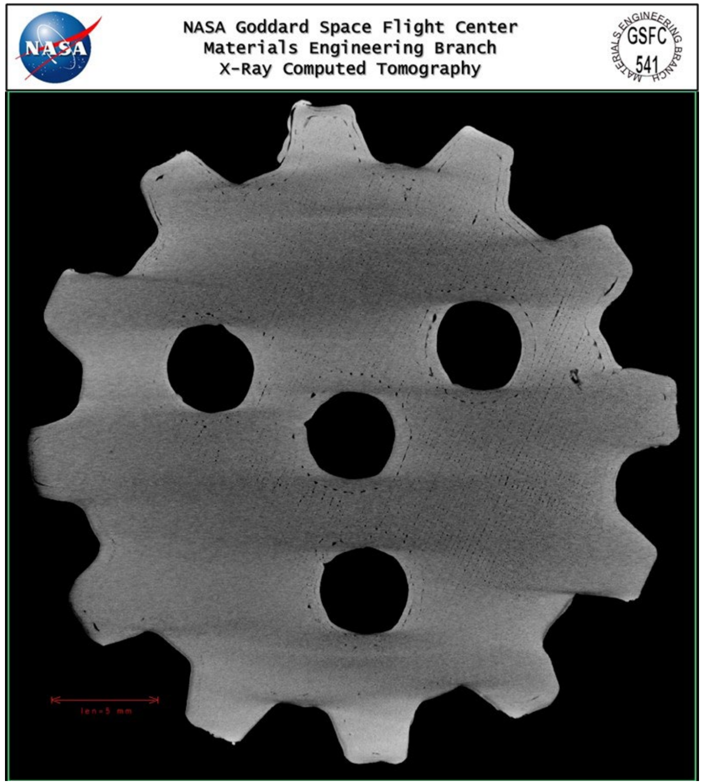
NDE for In-Space Manufacturing (ISM)

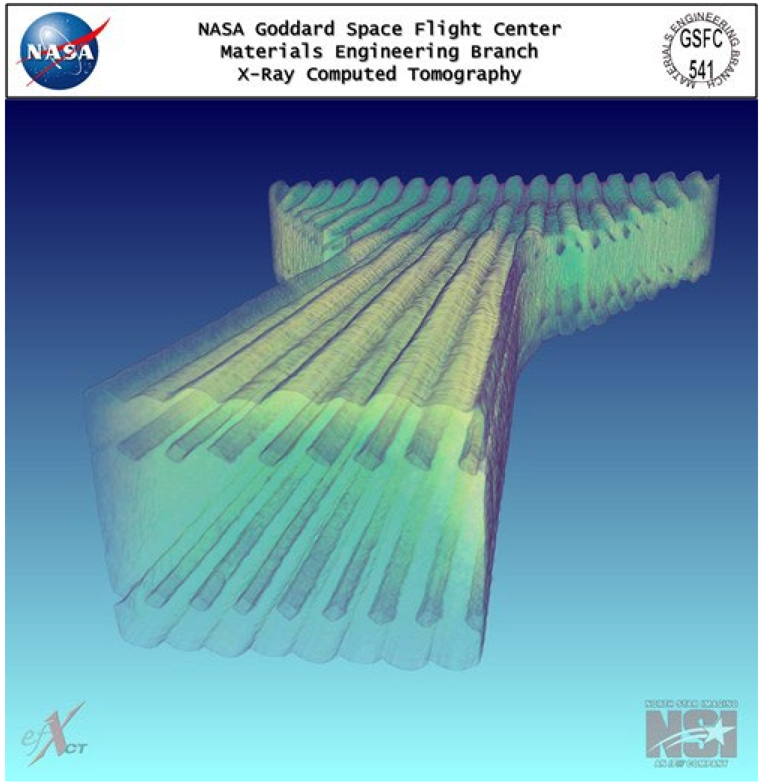
- GSFC NDE has worked with MSFC + Techshot to inspect preliminary AM ISM parts
- CT scan system on ISS would be crucial to certify parts for structural use applications
- These scans have been critical in establishing Key Performance Parameters (KPP) for in-space x-ray sources and imaging systems

GSFC x-ray Computed Tomography (CT) images of early prototype Techshot bound metal deposition parts (non-optimized builds).

Left image shows gear, with minor voiding in and around shells.

Right image is of a tensile coupon showing columnar cavities running along the length of sample.

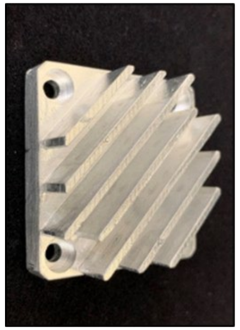




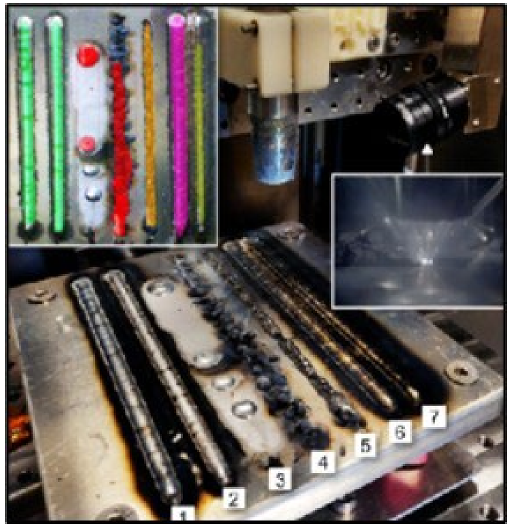
NDE for In-Space Manufacturing (ISM)

- Current metal AM tech. developments for ISM include in-situ monitoring
- Compact, in-space NDE tools will be needed for finished parts

Redwire (Made in Space) VULCAN



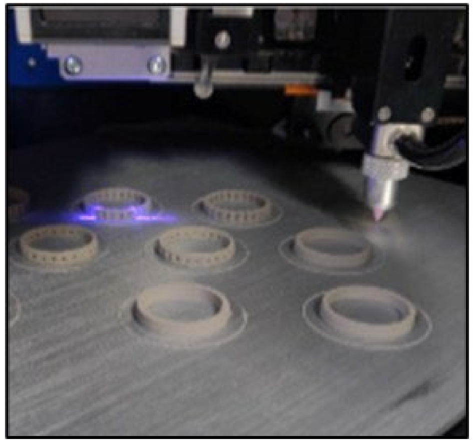
Wire-Arc Welding Additive Manufacturing + CNC + Weld Quality Grading Machine Vision

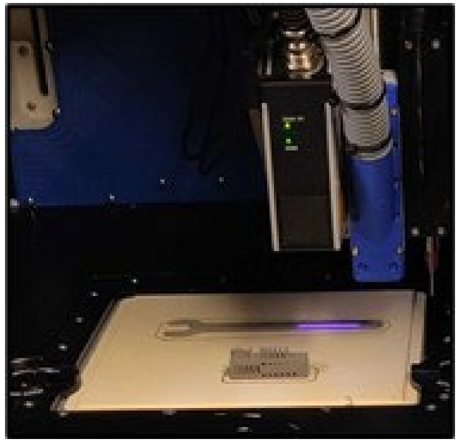


TechShot, Inc., FabLab

Bound Metal Deposition + Laser Profilometry

Ground-based prototype system

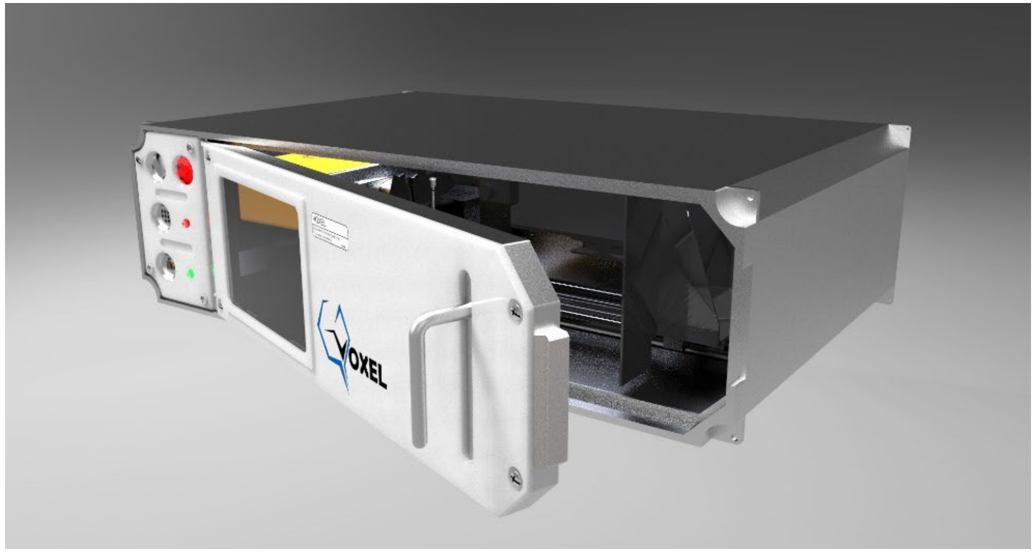




Images provided by Erin Lanigan/NASA-MSFC, with permission.

Recent efforts to assess X-Ray CT for operation in a space environment

- NASA Goddard Space Flight Center (GSFC) has led efforts to investigate In-Space X-ray Computed Tomography (CT) for multi-use applications, in collaboration with other centers
- Efforts include Concept Development and Trade Studies to assess feasibility for CT in different environments (ISS, lunar, Martian, crewed/non-crewed)
- Instrument Design Lab (IDL) study in late 2019 - early 2020 demonstrated core system feasibility and key requirements met for a pathfinder, prototype design, including deep dives into 12 major subsystems. New study to develop CEMA cost estimates by July ’23.
- Non-funded partnership agreement with North Star Imaging and collaborative efforts kicking off with Aerospace Corp. to explore “open CT” concepts



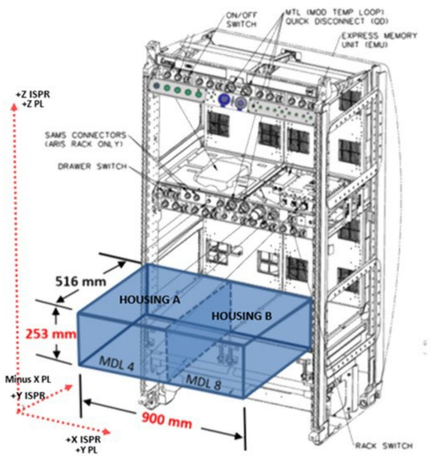
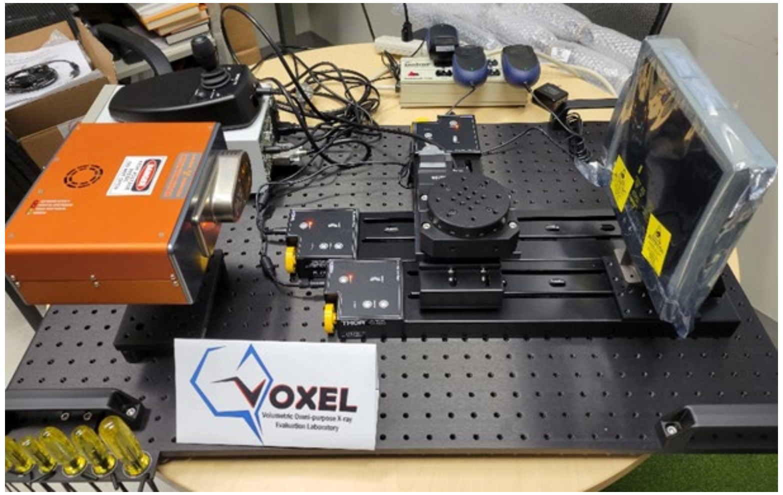
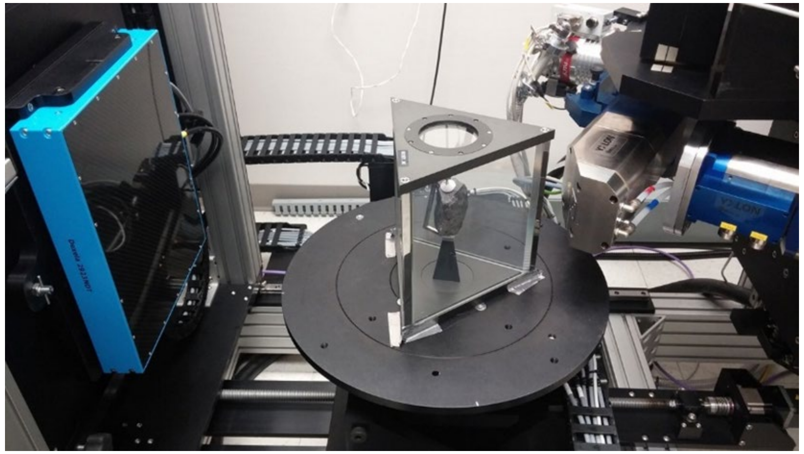


Image Credit: NASA

One potential venue for CT in Space could be on an ISS Express Rack (or similar setup on NASA Gateway). Shown above are an exterior rendering of "VOXEL" IDL design concept and generic Mid-Deck Locker (MDL) dimensions, representative of the size of such a system (e.g., could be single or double, as shown). Such a system would be human-tended, with astronauts loading samples. System could be controlled in space or remotely from Earth. Other concepts underway are non-cabinet-based systems, oriented for remote/telerobotic applications.

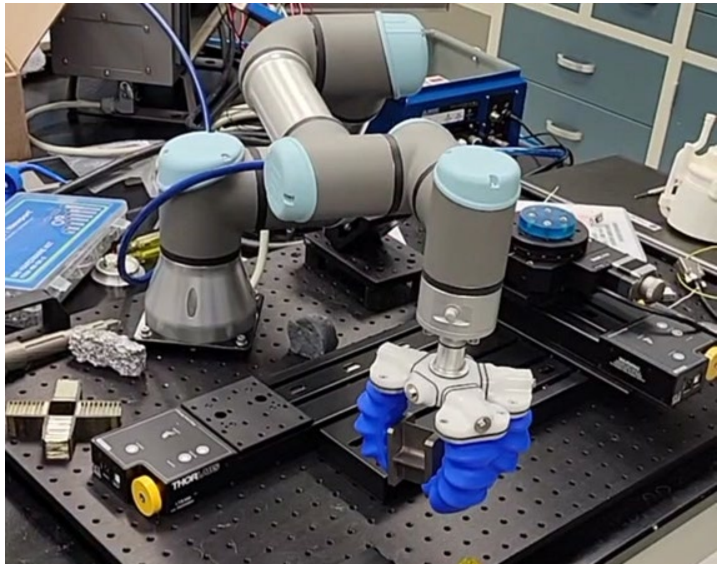
Recent efforts to assess X-Ray CT for operation in a space environment

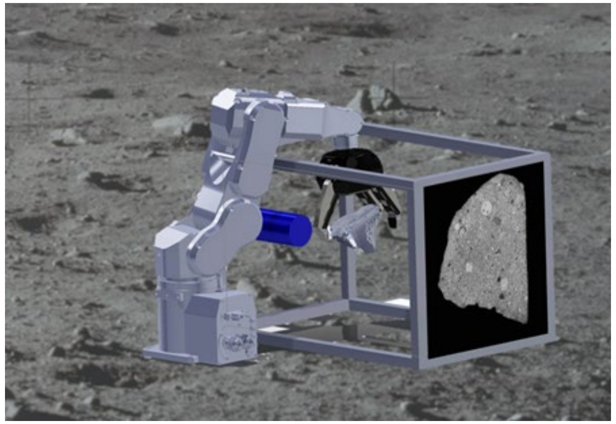




Conventional design with multi-axis manipulation and typical turn-table (upper) and laboratory CT scan of Apollo 11 lunar return sample (lower)

Moving towards robotic arm concept for more agile, remote use applications.

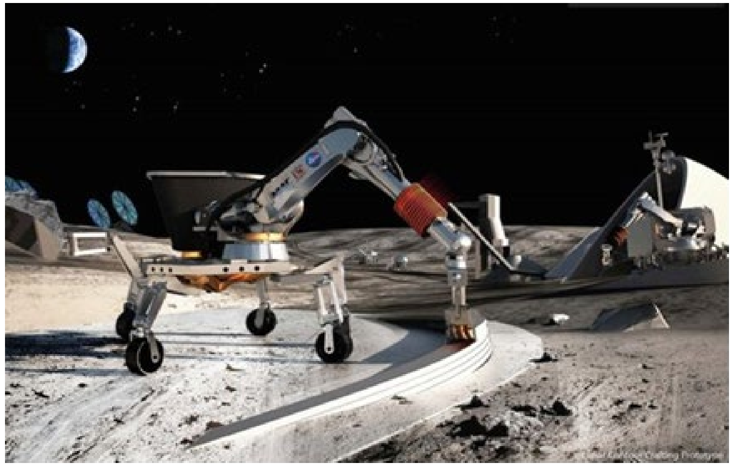




Early concept robotic CT currently under construction (upper) and crude artist representation of such a system in use for field use or remote applications on the lunar surface (lower)

Kennedy Space Center (KSC)

- Work in the KSC Surface Systems Office and at the University of Southern California under two NIAC awards§ have shown promising results with regolith materials for in-situ heat shields, bricks, landing/launch pads, berms, roads, and other structures that could be fabricated using regolith that is sintered or mixed with a polymer binder. The technical goals and objectives are to prove the feasibility of 3D printing additive construction using planetary regolith. Future KSC effort will explore the use of NDE to show that regolith structures have structural integrity and practical applications in space exploration.



Conceptual regolith structures being fabricated on the Moon (Khoshnevis)

§ Khoshnevis, B., *Contour Crafting Simulation Plan for Lunar Settlement Infrastructure Build-Up*, University of Southern California, Los Angeles, CA 90089, NASA Innovative Advanced Concepts (NIAC) Program Phase I Award, 2011.

Khoshnevis, B., *ISRU-Based Robotic Construction Technologies for Lunar and Martian Infrastructures*, University of Southern California, Los Angeles, CA 90089, NASA Innovative Advanced Concepts (NIAC) Program Phase II Award, 2012.

Motivation for In-Space NDE Tools*

Artist's concept of the Artemis Base Camp.

Image Credit: NASA

5 key Beneficiaries

- Manufacturing Quality Engineering and Hardware Quality Assurance(QA) / Failure Analysis (FA)
- Human Safety/Mission Assurance
- Additive Manufacturing (AM) & In-Space Manufacturing (ISM)
- In-Situ Resource Utilization (ISRU)
- Science Initiatives/Return Sample Triage

**Recent keynote presentation on this topic given at 16th ASNT International Symposium on Nondestructive Characterization of Materials on Aug 11, 2021: "In-Space Inspection Needs: Opportunities for advanced NDE tools such as x-ray CT for additively manufactured parts, in-situ resource utilization, geological applications, and more."*

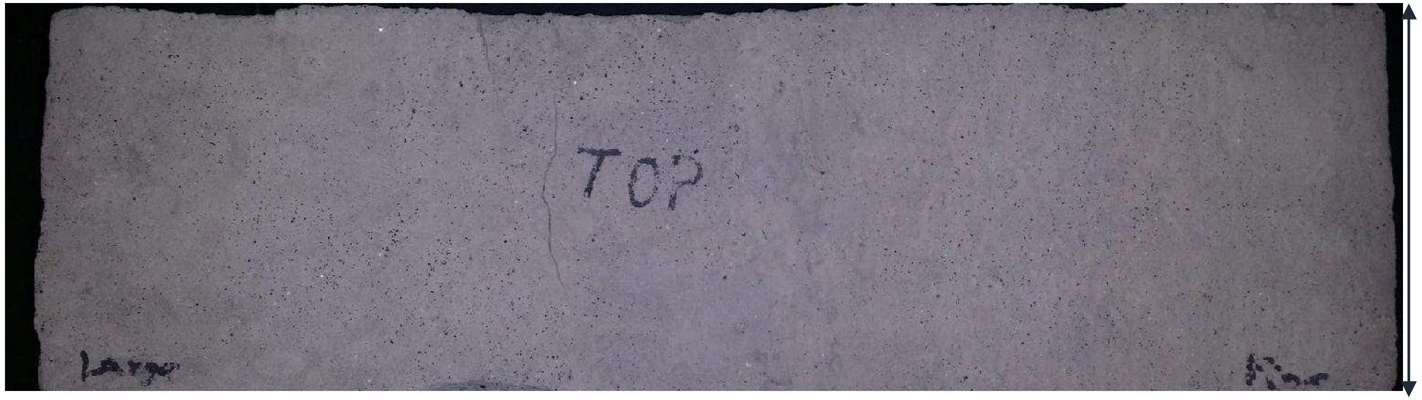
Moon to Mars Planetary Autonomous Construction Technologies (MMPACT)

- Goal: On-demand capabilities to protect astronauts and build infrastructure on the lunar surface with in-situ resource utilization to create launch/landing pads, habitats, shelters, roadways, etc.
- Lunar Demonstration ~2026

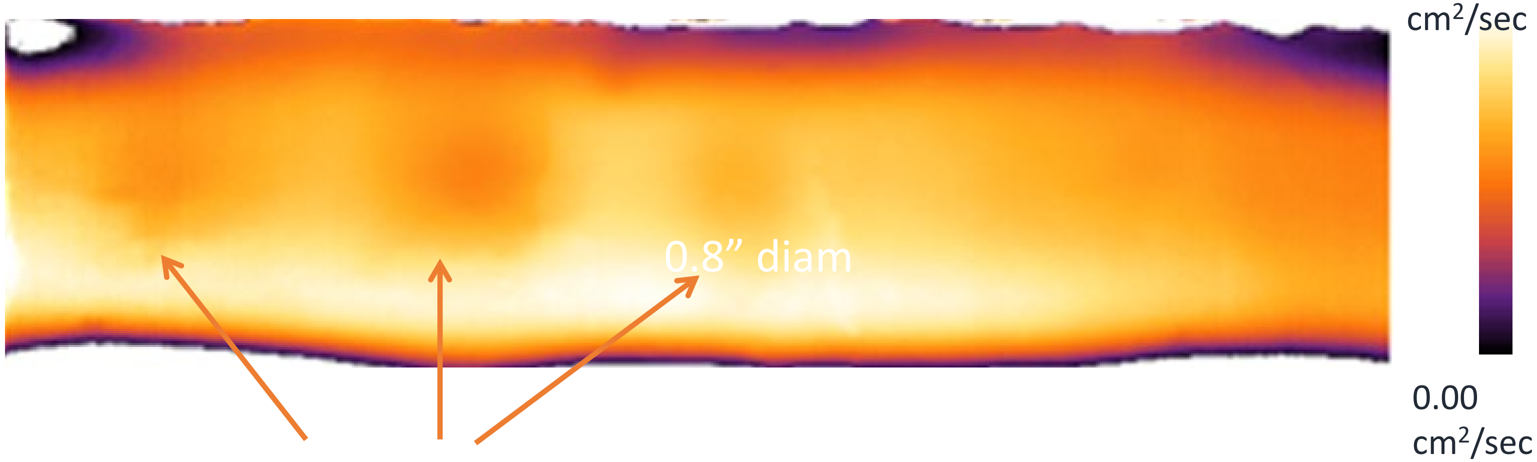
Material Inspectability Assessment

- Results
- Inspection shows three largest void defects
- Good surface emissivity and thinner samples or near surface voids = good candidate for thermal inspections during manufacturing
- Single sided thermal inspection data processing ongoing
- Additional samples expected

Top of Sample



Thermal Diffusivity Inspection Image



POC: Joseph Zalameda

Opportunities for Investment and Collaboration

Relevant links for partnership and funding opportunities

Partnering with NASA

- Partnership Office main page: https://www.nasa.gov/partnerships.html
- Field centers, lines of business and POCs: https://www.nasa.gov/partnerships/contact.html
- Links to key Tech. Development programs: https://www.nasa.gov/partnerships/opportunities.html

Technology Initiatives

- NASA Technology main page and overview: https://technology.nasa.gov/
- NEXT STEP program overview https://www.nasa.gov/content/nextstep-overview
- Technology road-mapping: https://www.nasa.gov/offices/oct/taxonomy/index.html
- Artemis Program Overview: https://www.nasa.gov/specials/artemis/

Funding Opportunities

- NASA SBIR and STTR Program (small businesses): https://sbir.gsfc.nasa.gov/
- Open NASA Solicitations and Contracts: https://sam.gov/content/opportunities
    - Formerly FedBizOps, or FBO
- Scientific and Technology Research Funding https://nspires.nasaprs.com/external/
- Space Technology Research Directorate (STMD) Programs: https://www.nasa.gov/directorates/spacetech/solicitations
- STMD Tipping Points program overview: https://www.nasa.gov/directorates/spacetech/solicitations/tipping_points

Neat site for 3D printing and models!

- https://nasa3d.arc.nasa.gov/

Thank you.

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***Jennifer C. Fielding**, America Makes, Youngstown, Ohio*
***Edward R. Generazio**, NASA NASA Langley Research Center, Hampton, Virginia*
***Brian Hughitt**, NASA HQ, Washington, DC*
***Justin S. Jones**, NASA Goddard Space Flight Center, Greenbelt, Maryland*
***Ajay Koshti**, NASA Johnson Space Center, Houston, Texas*
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***Richard W. Russell**, NASA Kennedy Space Center, KSC, Florida*
***Regor L. Saulsberry**, NASA White Sands Test Facility, Las Cruces, New Mexico*
***Miles Skow**, NASA Kennedy Space Center, KSC, Florida*
***David M. Stanley**, NASA Johnson Space Center, Houston, Texas*
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***LaNetra C. Tate**, NASA STMD, Washington, DC*
***Michael C. Waid**, NASA Johnson Space Center, Houston, Texas*
***James L. Walker**, NASA Marshall Space Flight Center, Huntsville, Alabama*

Why The Moon?

Presenter Biography

Eric Burke (NASA Langley NDE Branch)

- Eric Burke is a research and development physicist at NASA Langley Research Center where he serves as the Nondestructive Evaluation (NDE) Program manager for NASA's Office of Safety and Mission Assurance.
- With over 15 years of engineering experience within the NASA community, Burke focuses on the development and application of innovative materials and technologies. He is a Subject Matter Expert in the field of in-situ NDE on Additive Manufacturing (AM) parts and leads NDE activities and research on AM across all the NASA centers.
- Burke also leads the Small Business Innovative Research and Development program for technologies that will apply to future inspection of the International Space Station and deep space vehicles. Recent highlights include the delivery of a single side 3D x-ray system that is being used to scan the heat shield of the Orion spacecraft currently located at Kennedy Space Center. This prototype x-ray system is proving to be a critical piece for inspection of Avcoat® joints for the Orion program.
- Burke has received national recognition for excellence in the area of NDE and technology development including the NASA Early Career Achievement Medal and Launch Director's Award and a Silver Snoopy Award. Recently receiving 2 Space Flight Awareness (SFA) Flight Safety Awards.
- He holds four U.S. patents and has authored or co-authored nearly 20 conference papers. Prior to joining NASA in 2010, Burke worked as a research and development engineer for United Space Alliance and the University of Dayton. Burke holds both a Bachelor of Science degree and a Master of Science degree in mechanical engineering, solid mechanics, from the University of Dayton.
- Mr. Burke is an avid cyclist and 2-time Ironman Triathlete. In his spare time Mr. Burke coaches his sons and daughter soccer teams. www.linkedin.com/in/ericrburke
- Eric.r.burke@nasa.gov